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Throughput evaluation of an autonomous sustainment cargo container system

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MONTEREY, CALIFORNIA

THESIS

THROUGHPUT EVALUATION OF AN AUTONOMOUS SUSTAINMENT CARGO CONTAINER SYSTEM

by

Mingtze Yeh

December 2007

Thesis Advisor: Fotis Papoulias

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With the development of new concepts in military operations and reductions in manpower of our military forces, the promotion of autonomous systems has been pushed to the forefront. Autonomous containers will play an essential role in the ability to deliver logistical supplies to waterborne littoral vessels enabling them to maintain station and complete there military operations while reducing the threat to personnel. Programmed to deliver supplies to a specified local in a reasonable timetable, these containers will play an essential role to vessels such as Riverine Warfare patrol craft, Special Operations craft and Coast Guard search and rescue boats. Development of a successful autonomous system that can deliver logistical supplies in littoral human threat arenas would serve as an immense reduction in logistical supply costs. The research that is to be conducted will focus on the unique characteristics of an autonomous sustainment cargo container and its throughput evaluation. Use of geometric data and static stability is analyzed and compared. In depth analysis primarily focuses on the hull characteristics of the container and whether subtle alterations to the bow and stern units reduce the resistance and increase the efficiency of the deliverability rate of the autonomous system.

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THROUGHPUT EVALUATION OF AN AUTONOMOUS SUSTAINMENT CARGO CONTAINER SYSTEM

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

With the development of new concepts in military operations and reductions in manpower of our military forces, the promotion of autonomous systems has been pushed to the forefront. Autonomous containers will play an essential role in the ability to deliver logistical supplies to waterborne littoral vessels enabling them to maintain station and complete there military operations while reducing the threat to personnel. Programmed to deliver supplies to a specified local in a reasonable timetable, these containers will play an essential role to vessels such as Riverine Warfare patrol craft, Special Operations craft and Coast Guard search and rescue boats. Development of a successful autonomous system that can deliver logistical supplies in littoral human threat arenas would serve as an immense reduction in logistical supply costs. The research that is to be conducted will focus on the unique characteristics of an autonomous sustainment cargo container and its throughput evaluation. Use of geometric data and static stability is analyzed and compared. In depth analysis primarily focuses on the hull characteristics of the container and whether subtle alterations to the bow and stern units reduce the resistance and increase the efficiency of the deliverability rate of the autonomous system.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ABBREVIATIONS

ISO	International Organization of Standards
ASCC	Autonomous Sustainment Cargo Container
LCU	Landing Craft Utility
LCAC	Landing Craft Air Cushion
HSV	High Speed Vessel
AEPCO	Advanced Engineering & Planning Corporation, Incorporated
NSWC	Naval Surface Warfare Center

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I. AUTONOMOUS SUSTAINMENT CARGO CONTAINER (ASCC) DESIGN CONCEPT

A. BACKGROUND OF CONCEPT AND DESIGN

1. Background and Introduction to Delivery

With the development of new concepts in military operations and reductions in manpower of our military forces, the promotion of autonomous systems has been pushed to the forefront. As the emphasis of combat warfare has been placed heavily in the littorals, it is getting more and more arduous for the United States military to maintain a presence without logistical support. Waterborne craft such as mechanized Landing Craft Utility (LCU), Landing Craft Air Cushion (LCAC), and High Speed Vessels (HSV) have been used for logistical delivery. All three of those types of delivery vehicles are very capable in their abilities to transport logistics to the end user with speed and efficiency; however, they have a human risk of life element for those onboard within them. It is now more imperative than ever that the lives of military men and women not become endangered, as they are the United States Department of Defense's most expensive commodity. Thus, the necessity for an autonomous system that can deliver logistical supplies has become more important than ever in order to maintain military presence in foreign soil.

An autonomous vehicle is a self-piloted vehicle that does not require an operator to navigate and accomplish its tasks. As the necessity to protect human life grows, the need for autonomous vehicles will grow as well. The idea or concept for an autonomous logistical delivery method is not brand new though. The concept for an autonomous system that could be utilized as a delivery method can be traced far back into history. In the past, waterborne vessels would simply strategically place boxes of logistical supplies, needed by troops on shore, into the waterways and allow the strength of the current to push the supplies onto the beach.

Currently, the United States Navy has the capability of using Airborne and Undersea vehicles within its arsenal. The use of an ASCC delivery system and using it for mission applications could prove to be very advantageous. The logistical interface of sea basing will no longer needed. With the reduction of sea basing comes with it the reduction of bulk cargo constraints and cargo breakouts, manpower and the addition time savings. The mission application has immense appeal to Joint Logistics over the Shore (JLOTS). The reduction in manpower requirements, enhancements of personnel safety, and reduction of local infrastructure requirements are its greatest attractors.

Advanced Engineering & Planning Corporation, Incorporated (AEPCO) has proposed a solution which aims to reduce manpower requirements for various littoral vessels as well as enhance personal safety by transporting cargo containers from the parent ship to shore using an autonomous system aboard the container [8]. This report is being conducted in conjunction with Naval Surface Warfare Center (NSWC) Carderock Division and their findings. The autonomous containers system will soon play an essential role in the ability to deliver logistical supplies to waterborne littoral vessels or embarked troops ashore enabling them to maintain station and complete there military operations while reducing the threat to human life.

2. Introduction to Design Concept

The risk of endangerment to military personnel could be eliminated with the development of the capability to autonomously move International Organization for Standardization (ISO) cargo containers from a delivery ship to the littoral environment or onshore and such an endeavor would be highly desirable. The envisioned mission concept of the ASCC is rather simple. An ideological mission would include delivery of logistical supplies by the ISO and return of the container to delivery vessel. Besides the ISO container itself, the other components necessary for mission success would include the propulsion system, electronics package, and a ballast assembly. The elimination of risk to human life is the strongest attractor for the development of an autonomous

logistical system. Concept exploration aims to answer the speed-power performance of the system, which involves exploring engine selection, fuel load, range estimation, bow and stern design, etc [8].

a. Idealized Example of Delivery

A logistical delivery vessel would be stationed off the shoreline a specified distance, as to not be with enemy firing range, nominally 25 plus nautical miles away. The logistical vessel would then place an Autonomous Sustainment Cargo Container into the water. The container would then travel along a defined route until it reaches its selected area. The delivery profile of going from ship-to-shore would be the most basic and simplest of the design concept criteria. Once onshore and after offload of logistical supplies, the ASCC will return from its shore location to the location of the logistical delivery vessel. Figure 1 below shows a scenario in which there are possible obstacles to personnel and mission typically encountered when trying to deliver logistical supplies. Additionally, Figure 2 shows the current method of how logistical support is being conducted and the risks involved.

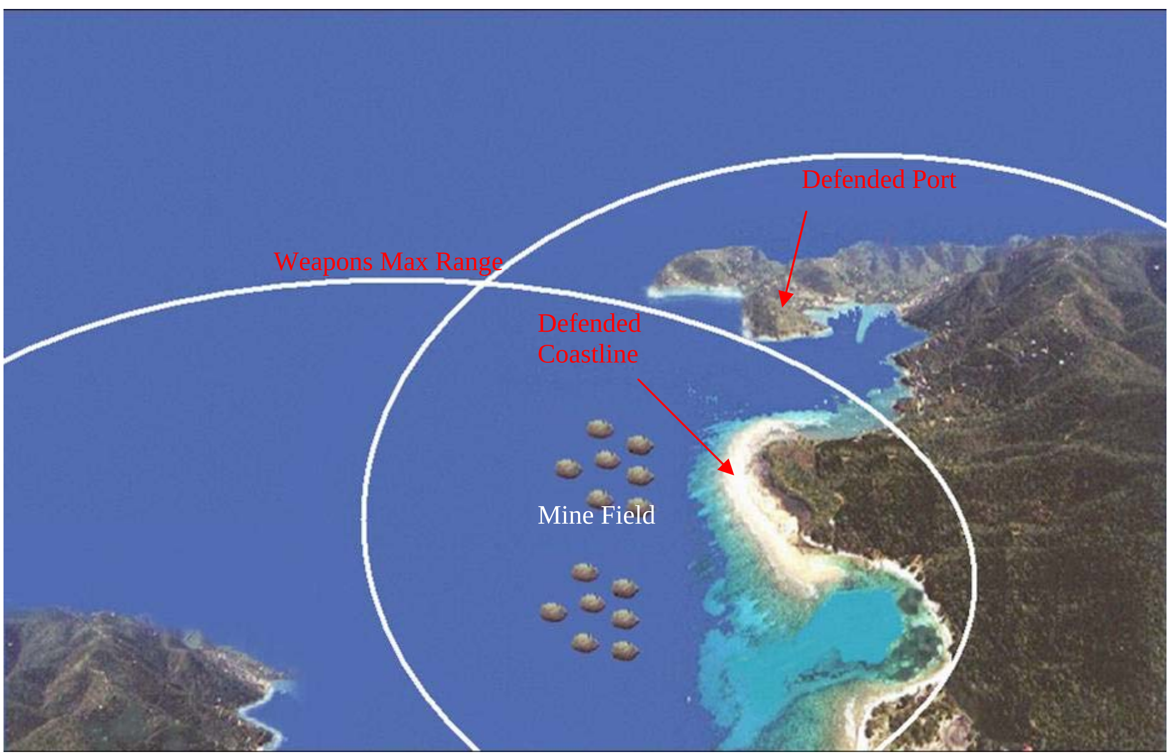

Figure 1. Potential Deployment Area (From Ref 3)

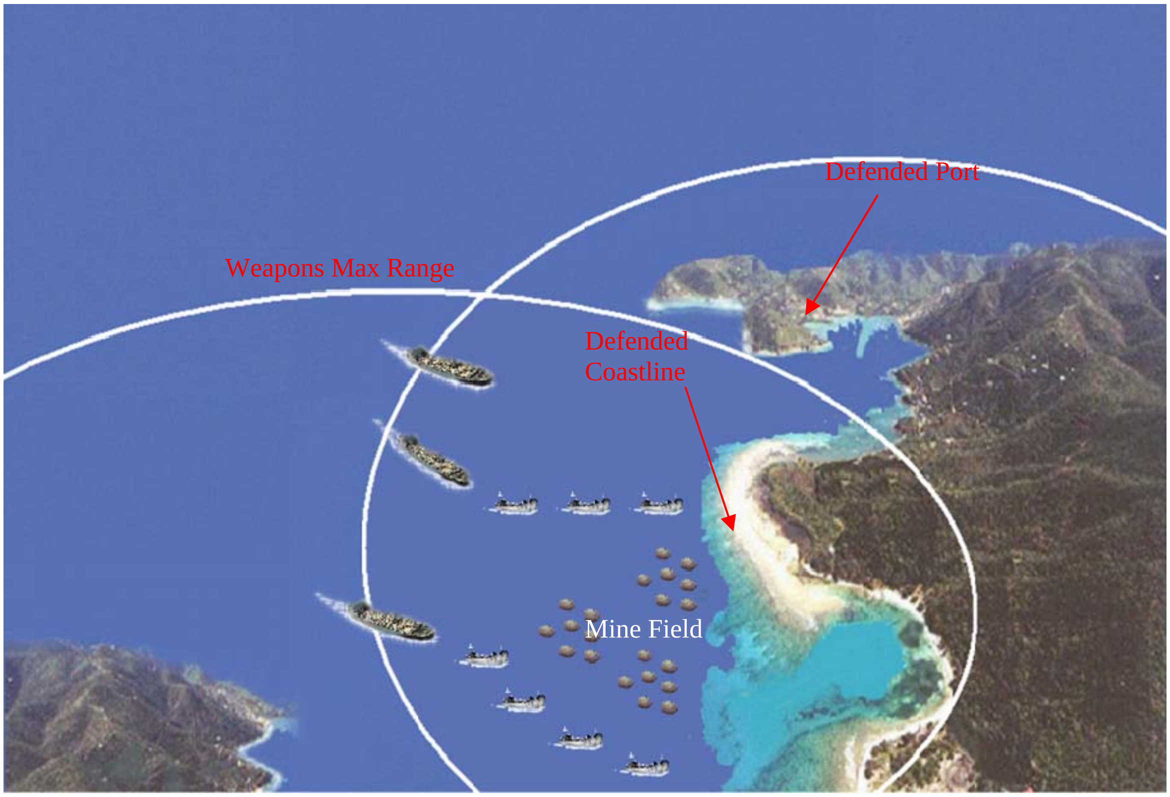

Figure 2. Potential Dangers to Personnel (From Ref 3)

It can be seen that the possible dangers and obstacles involved with logistical deliveries are inherently abundant. With the use of an Autonomous Sustainment Cargo Container (ASCC) system, personnel endangerment can be severely reduced in comparison to that of the current logistical supply delivery system. Figure 3 shows how endangerment of life to personnel can be avoided altogether with the implementation of the ASCC system for passive logistical deliveries.

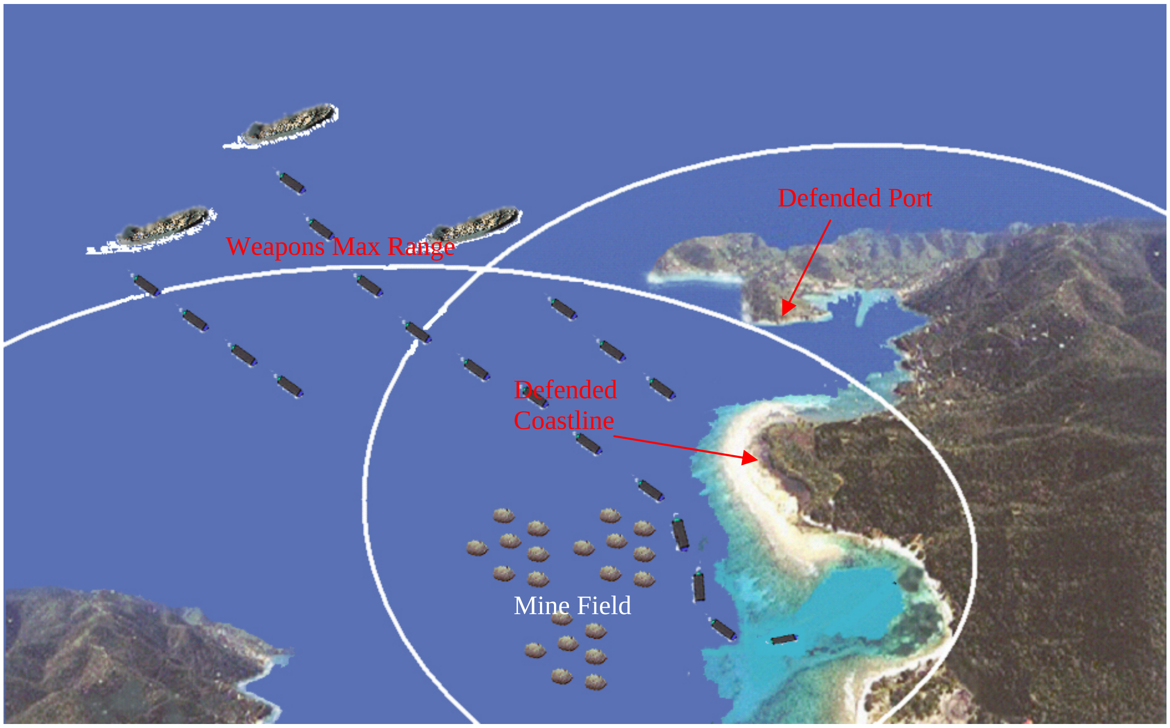

Figure 3. Obstacles of Logistical Delivery (From Ref 3)

b. Subsystem Components

The International Organization for Standardization (ISO) cargo container is the core structural component of the Autonomous Sustainment Cargo Container. The commercial cargo containers, which will be the ones utilized for this report, are manufactured according to specifications set forth by the International Organization for Standardization, known as the ISO. These ISO cargo containers have specifications which include standards for strength, water-tightness, mobility, and security. The size of ISO containers come in five common sizes, however the 20 foot container will be the size specifically referred to and based upon for this report. In addition, the ASCC delivery system will comprise of three other subsystems which is to include an electronics package, propulsion system, and ballast assembly.

The electronics package that will be outfitted onto the container is envisioned to be programmed prior to its insertion into the water and will be designed to guide the ISO container to the specified location of delivery. The propulsion system will be the powering force that “drives” the ISO container ashore or to its designated area.

The ballast assembly will be used as a means to control the stability as well as other sea keeping performance variables. The three planned subsystems modules are envisioned to be incorporated onto the ISO container which would enable the ASCC system to succeed. All three subsystems are tasks that are dependent upon one another. A propulsion unit cannot be selected until a powering range is determined. A powering range based on the resistance data cannot be determined until the configuration of the vessel is established. Full circle, the configuration cannot be explicitly stated until the propulsion and bow unit dimensions are established [8]. All of the components to be implemented onto the autonomous system will be commercial off the shelf (COTS) with an open-architecture for the entire life-cycle of ASCC. NSWC Carderock Division is in process of exploring the three previously mentioned subsystems and associated tasks. The use of COTS equipment from military or commercial programs will minimize cost of the overall system, with universality (world-wide adaptability). Additionally, the subsystem components modular and may be removed. In comparison, the loss of a cargo container is minute to that of human life. A typical ISO container is shown below followed by how a cargo container would look with the electronics package, propulsion system, and ballast assembly.

Figure 4. Typical ISO Container (From Ref 8)

Figure 5. Envisioned ASCC Module (From Ref 3)

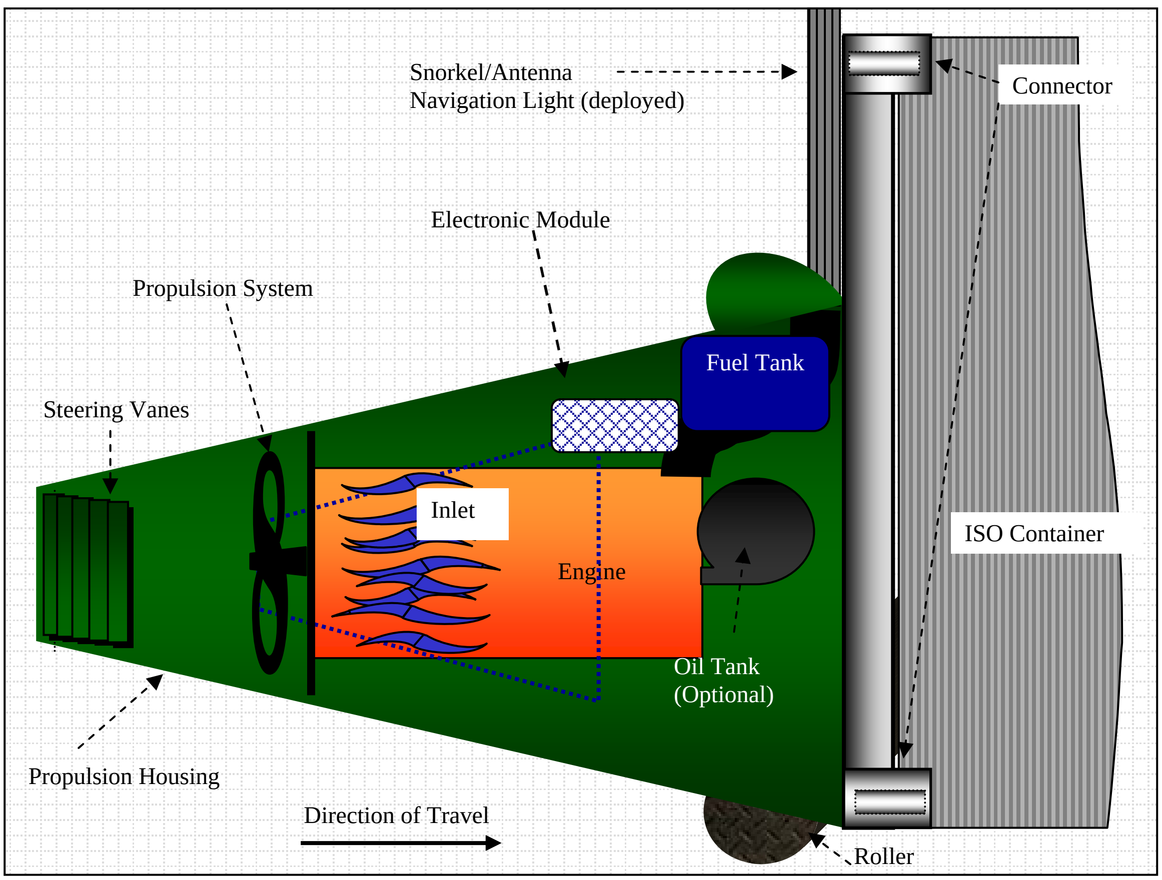

Figure 6. Internal View of Propulsion System (From Ref 3)

There are many variables and measures that are in need for consideration or must be assumed for accuracy of this report which will be used to inherently fulfill the functional tasking of the design scheme. Universality is inherent to the component

selection and the design interface. Some of the key parameters included but not limited to are: weight, payload, power output, and resistance through the water. The dry cube, ISO cargo container that will be used have specific dimensions of 20’ x 8’ x 8’6” with maximum payload of over 28 metric tons. With the resistance and powering data not specifically defined, the report will assume that the propulsion system will be able to provide speeds of up to 25 knots. The resistance of the container through the water will assumed to be constant throughout but varies dependent upon the bow and stern designs of the ISO container. The report will solely focus on and evaluate how cargo containers with differing bow and stern unit designs will inherently affect the throughput of logistical delivery of an Autonomous Sustainment Cargo Container delivery system. With a constant payload and power output, how will the variations of hull design maximize the throughput efficiency of an Autonomous Sustainment Cargo Container delivery system?

II. ASCC VERSUS OTHER LOGISTICAL SUPPLY DELIVERY VEHICLES

A. LOGISTICAL DELIVERY VEHICLES

1. LCU 2000 Class

The use of Landing Crafts Utility (LCU) which dates back to World War II, were originally used for amphibious assaults where its mission was to land/retrieve personnel and equipment (tanks, artillery, equipment, motor vehicles) during amphibious operations. Today, the LCU is used in a wide variety of missions, in particularly, moving containers, general, and vehicular cargo to the objective area. With a cargo capacity of 350 tons and a deck area of 2500 square feet, they have room for five M1 Main Battle Tanks or 30 - 20 feet containers. The LCU 2000 also has the capability to carry cargo from deep draft ships to shore ports or areas too shallow for larger ships. Typically used for unit deployment and relocation, it has a bow ramp for Roll-on/Roll-off cargo, and a bow thruster to assist in beaching and beach extraction [7]. A table of its features is listed in the table below.

Length overall	174 feet
Beam	42 feet
Draft	9 feet (loaded)
Displacement	1087 long tons (loaded)
Deck area	2,500 square feet
Payload	350 tons
Range	6,500 nautical miles (loaded)

Table 1. LCU Specifications (From Ref 9)

Figure 7. LCU 2000 Class (From Ref 9)

2. LCAC

The development of the Landing Craft Air Cushion (LCAC) was one of the most dramatic and revolutionary innovations for the United States military in modern amphibious warfare technology. Not only did it provide the capability to launch amphibious assaults from points over the horizon, but it also enabled the capability to use the LCAC as a logistical delivery vehicle as well. Its utilization has allowed the logistics to be placed on the beach with speed and efficiency.

Previously, landing craft had a top speed of approximately eight knots (LCU) and could cross only 17% of the world's beach area. With to its tremendous over-the-beach capability, LCAC is accessible to more than 80% of the world's coastlines [6]. The LCAC is capable of carrying a 60 ton payload, up to 75 tons in an overload condition, all while moving at speeds over 40 knots [6]. It also has a substantial fuel capacity of approximately 5000 gallons but averages using 1000 gallons per hour [6].

Figure 8. LCAC Landing (From Ref 6)

The LCAC, like all "hovercraft," rides on a cushion of air. The air is supplied to the cushion by four centrifugal fans driven by the craft's gas turbine engines. The air is enclosed by a flexible skirt system manufactured of rubberized canvas. Unlike the Surface Effect Ship (SES), no portion of the LCAC hull structure penetrates the water surface; the entire hull rides approximately four feet above the surface [6]. LCACs can operate regardless of water depth, in shallow or adverse tides, and withstand possible underwater obstacles from one to two miles offshore to a range of up to 50 miles.

However, times have changed where the enemy and environment of the world today reflects increased uncertainty involving origins of threats and the possible locations of attacks. “Asymmetric threat” is now a familiar term widely used in the lexicon, and terrorist actions are a frequent occurrence [6]. The threat environment has moved from the “blue water” to “brown water,” or littoral regions, placing emphasis on power projection, force protection, and expeditionary operations in littoral areas. The means by

which logistics are delivered can be vastly improved by the use of an autonomous system. Even with this terrorist deterrence, logistical delivery is still a must.

3. High Speed Vessel (HSV)

Since October 2001, the Marine Corps and Navy have been conducting concept based experiments with the Joint High Speed Vessel (JHSV) in order to assess their capabilities and limitations within the context of sea basing and Operational Maneuver from the Sea (OMFTS) [7]. Experiments are being explored for commercially available high-speed, shallow draft vessels with advanced hull, propulsion, and communications technologies, the High Speed Vessel (HSV-2 Swift) currently being one of those vessels.

Figure 9. HSV (From Ref 7)

The HSV has the ability to provide a mission essential asset that will support operational movement, repositioning and sustainment of combat forces. The vessel gives the theater Commander a high-speed, intra-theater sealift capability to support all theater engagement requirements within his Area of Responsibility (AOR) while also providing

the capability to operationally move and maneuver combat ready unit sets from staging sites into the forward areas and follow-on sustainment [7]. With the ability to carry 600 tons of cargo, travel in excess of 40 knots and have a fully loaded range of 4,500 nautical miles, the vessel can perform trans-oceanic crossings without replenishing, essential for over the horizon operations.

4. Autonomous Sustainment Cargo Container System (ASCC)

In the past, cargo operations consisted of moving numerous small items like boxes, drums, and crated goods, using cranes and physical labor to load and off-load these from the dockside transport ships. Although dockside transport vessels are relatively efficient, it has become common place to move goods to or from undeveloped shorelines. Broadly speaking, the role of the Navy and Marine Corps in the U.S. military is to provide credible, sustained combat power from the sea when and where it is needed [4]. Many future naval combat operations are likely to be in the littorals, that is, close to shore, in order to project power ashore and to provide an umbrella of defense for forces ashore [4]. In the littorals, naval operations are expected to be contested with mines, diesel submarines, swarms of small boats, and anti-ship cruise missiles [4]. Marine expeditionary operations can be contested by shore batteries, ground forces, and mines in the surf, on the beach, and inland [4]. Therefore for U.S Naval forces, the classical terms “blue water” threat and “major threat axis” no longer hold the significance they once did.

With the ever increasing number of undeveloped shorelines the United States Military continually facing the role of the traditional dockside transport or any other manned vehicle has become a major hazard. Considering these many reasons, it is time to transform the military delivery system of logistical supplies to autonomous. The ASCC system would become an immensely effective tool for all services of the United States military. While all three before mentioned methods of transport for logistics have proved to be efficient both in speed and payload, they do not offer the ability to eliminate the threat to human life. Although the price of an autonomous vehicle has not been thoroughly established, the price of the components and subcomponents are very minute and are of no comparison in monetary value to that of military personnel.

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III. ALTERNATIVE ALTERATIONS TO THE ASCC AND THEIR EFFECT ON RESISTANCE

A. ALTERNATIVE ALTERATIONS

1. Bow Units

The Autonomous Sustainment Cargo Container System will be comprised of an ISO cargo container as its core component. The throughput analysis and evaluation of overall efficiency will come from its three subcomponents. The electronics package and propulsion system are the main components, which are to be enclosed within the stern unit while the ballast assembly will inherently make up the bow unit. The basic dimensions and loading conditions for the 20 feet ISO cargo container have been given and set in order to conduct this analysis and coincide with documentation from AEPCO, Inc. All of the various bow and stern unit lengths for the cargo container will not exceed 8 feet (max height and width of ISO container which modules are to be stored in) [8]. The following table outlines the basic characteristics of a 20 feet ISO cargo container, Figure 4, loaded to 80 percent of its maximum payload conditions with numeric calculations.

▲ [lbs]	42316
Length (L) [ft]	19.875
Beam (B) [ft]	8
Height (H) [ft]	8
▲ [LT]	18.891
▼ [ft^3]	661.188
Draft (T) [ft]	4.158
Length-to-Beam Ratio (L/B)	2.48
Beam-to-Draft Ratio (B/T)	1.92
L’ [ft]	35.875
L’/B	4.48

Table 2. Standard 20’ ISO at 80% Payload (From Ref 8)

A report preliminary study from The University of Michigan, College of Engineering, was used to determine initial resistance data for possible configurations, examining six vessels in total which include a parent hull (a rectangular box-barge vessel) [8]. Variations of the parent hull were also conducting by adding on bow units only, stern units only, bow and stern units combined, and parallel mid-body [8]. These variations are shown in the figure below.

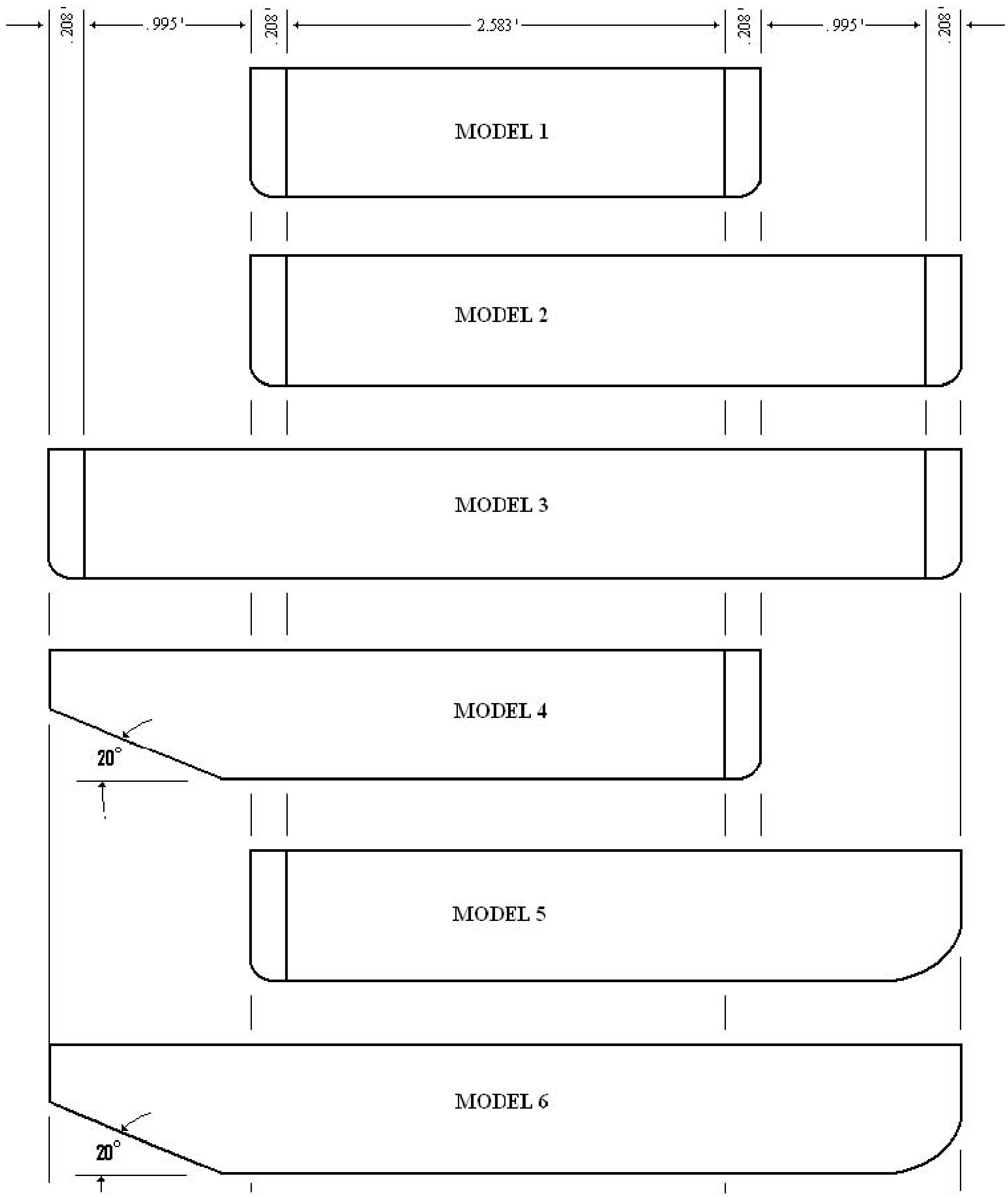

Figure 10. Initial Model Designs (From Ref 8)

	Bare	M1	Bare w/ units	M6
L [ft]	19.875	3.00	35.875	5.41
B [ft]	8.0	1.20	8.0	1.20
L/B	2.48	2.50	4.48	4.50
T [ft]	4.16	0.6	-	0.4 or 0.6
B/T	1.92	2.00	-	2.0 or 3.0

Table 3. Measure of Model Designs (From Ref 8)

The draft for the bare container plus bow and stern unit configuration is undetermined since there are a couple of unknowns, such as the weight of the final propulsion unit as well as the volume characteristics of the bow and stern unit [8]. From the University of Michigan study conclusions were reached as to the feasibility of major resistance reductions, effects of drastic variations in hull proportions, and the presence of scale effects [8]. The report's "Model 1" was scaled to that of a bare 20 feet ISO cargo container while "Model 6" was used as an adequate representation of a similarly scaled version of a 20 feet ISO cargo container with bow and stern units attached.

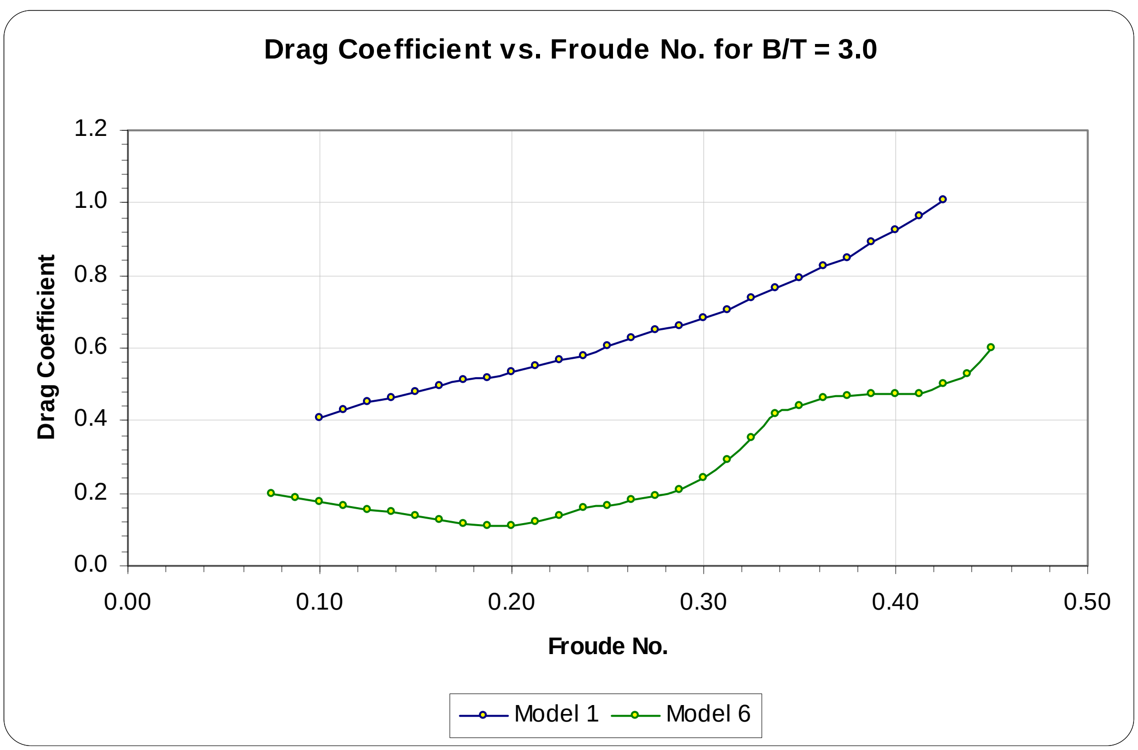

Figure 11. Comparison of Model 1 and Model 6 with B/T 3' (From Ref 8)

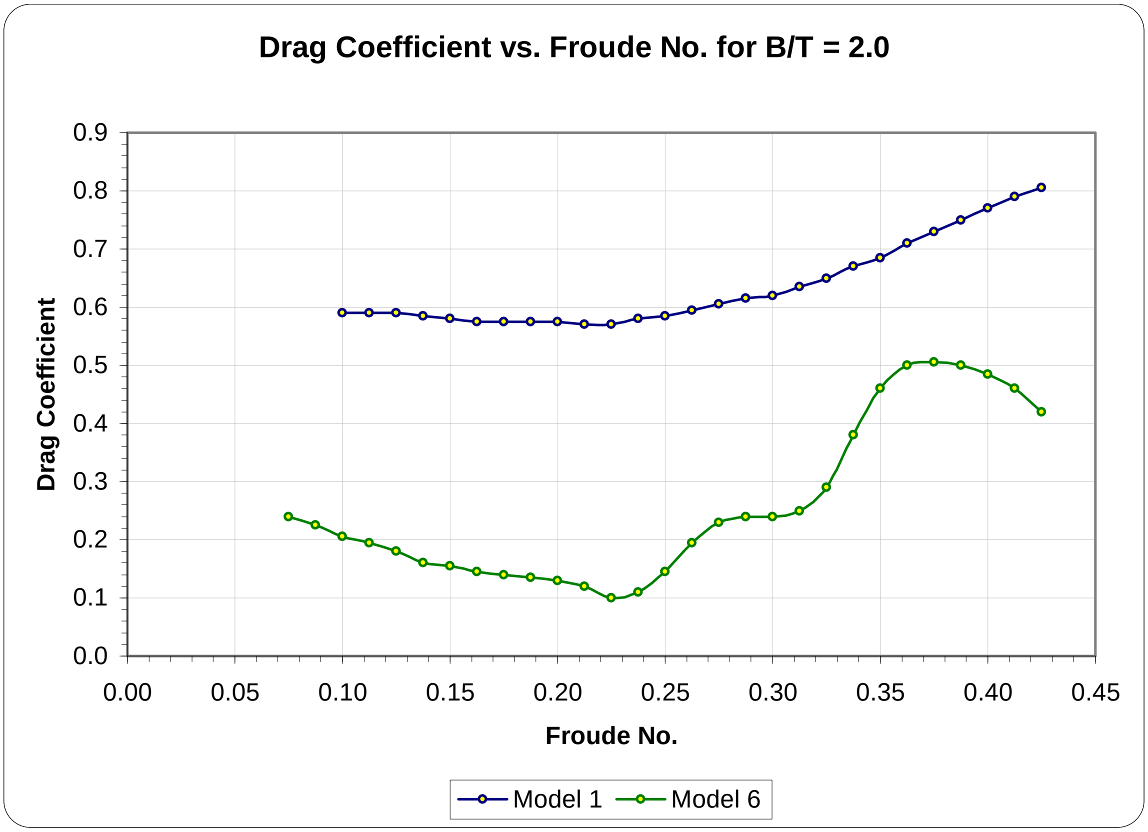

Figure 12. Comparison of Model 1 and Model 6 with B/T 2' (From Ref 8)

The drag coefficient versus Froude number in the figures above for beam to draft ratio of three feet and two feet show how the addition of bow and stern units to a standard ISO would reduce resistance through the water. Introduction of a "bulb" protrusion on the bow reduces drag [10]. Adding a second bulb to the stern is still better [10]. The figures above illustrate the resistance data taken for the two models of differing beam to draft (B/T) ratios and prove the importance and need of having a bow and stern unit attached to a cargo container, essentially a box barge, as opposed to driving a bare cargo container vessel alone through the water.

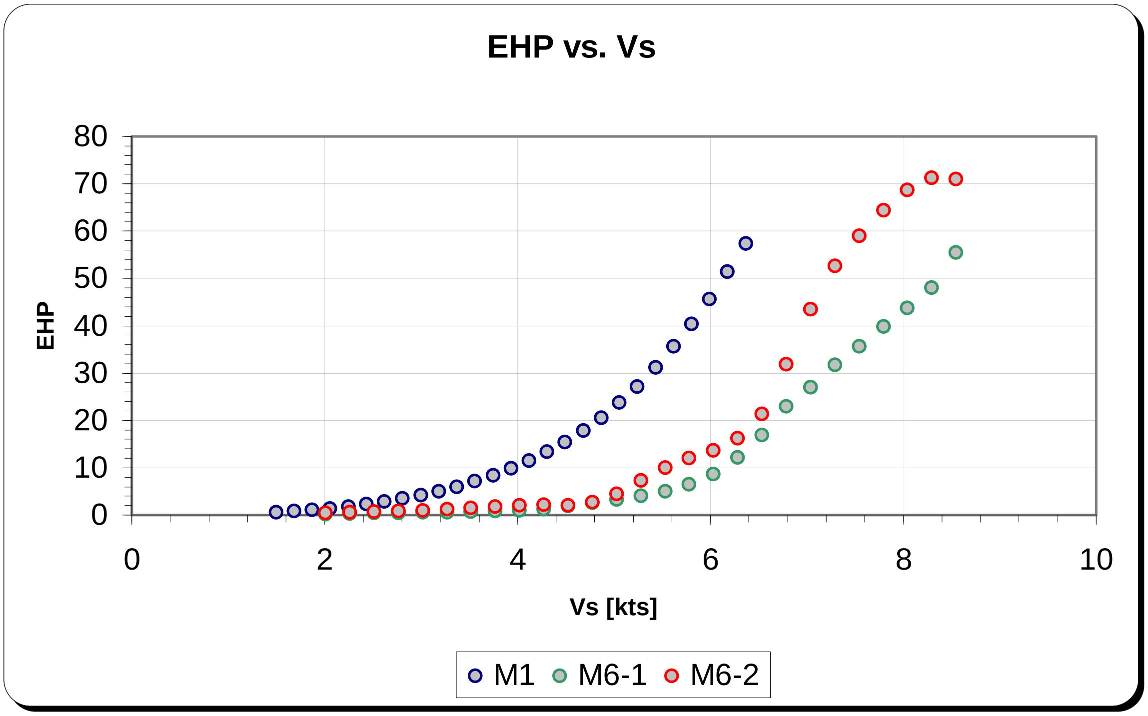

Figure 13. Effective Horsepower with B/T of 3.0 and 2.0 (From Ref 8)

The above figure shows a combination of both beam to draft ratios of 3.0 and 2.0 for the initial Model 6 design, shown as M6-1 and M6-2, respectively. Less horsepower will be needed to produce faster speeds due to reductions in drag force created by the addition of bow and stern units.

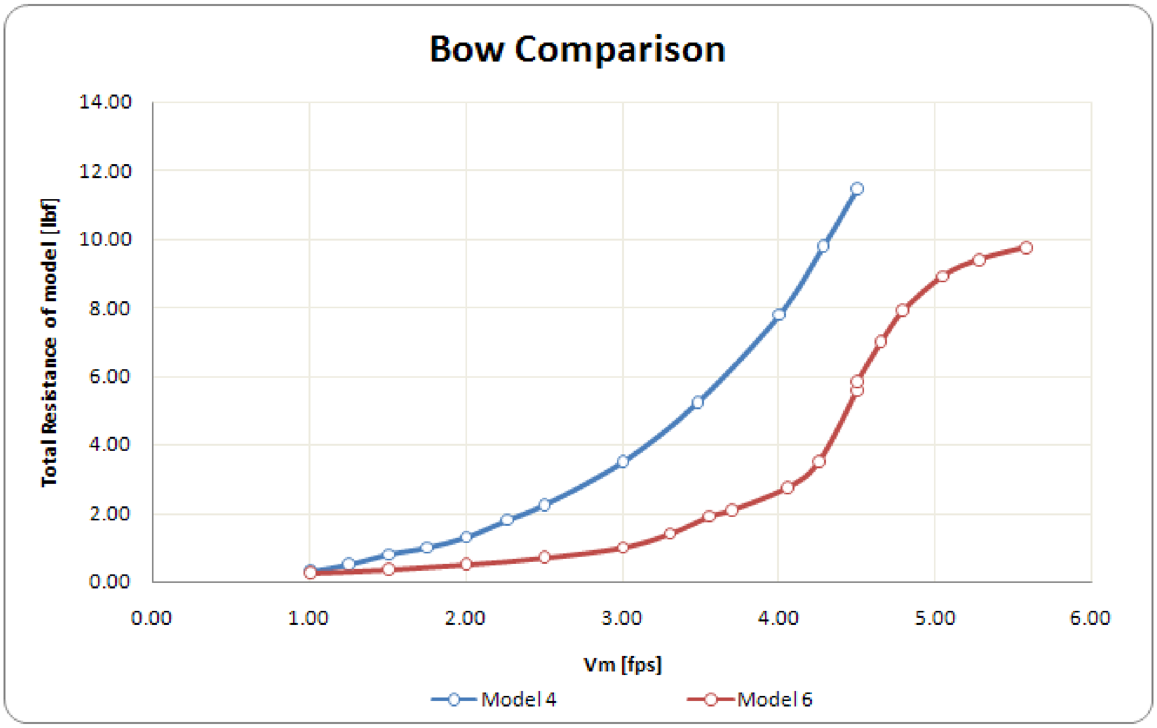

Figure 14. Model 4 with and without Bow Unit (From Ref 8)

It can be seen that the cargo container would benefit from having a bow and stern units attached; however, it is still not clear yet what the final design should or will be, or which unit (bow or stern) should receive design priority [8].

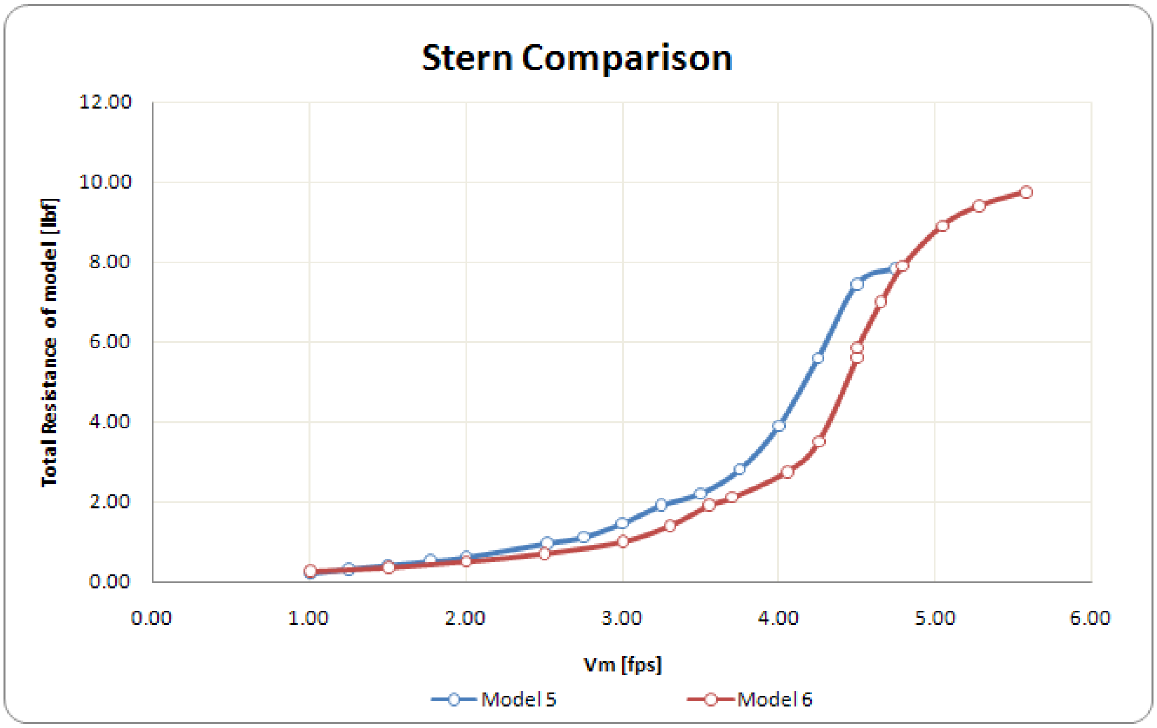

Figure 15. Model 5 with and without Stern Unit (From Ref 8)

From here, the paper will exclusively focus on how alternative alterations in the bow and stern unit designs will affect the resistance of travel through water and which design or combination of designs will maximize throughput efficiency. The below illustration demonstrates how the shape effects drag resistance which in turn impacts the resistance coefficient. Stokes proved that with the use of Reynolds number and Navier-Stokes equations that, “Stoke Flow” the balance between pressure gradients and viscous stress, has an immense impact in reducing drag with streamlining [10]. Further discussions of resistance will analyzed in future chapters.

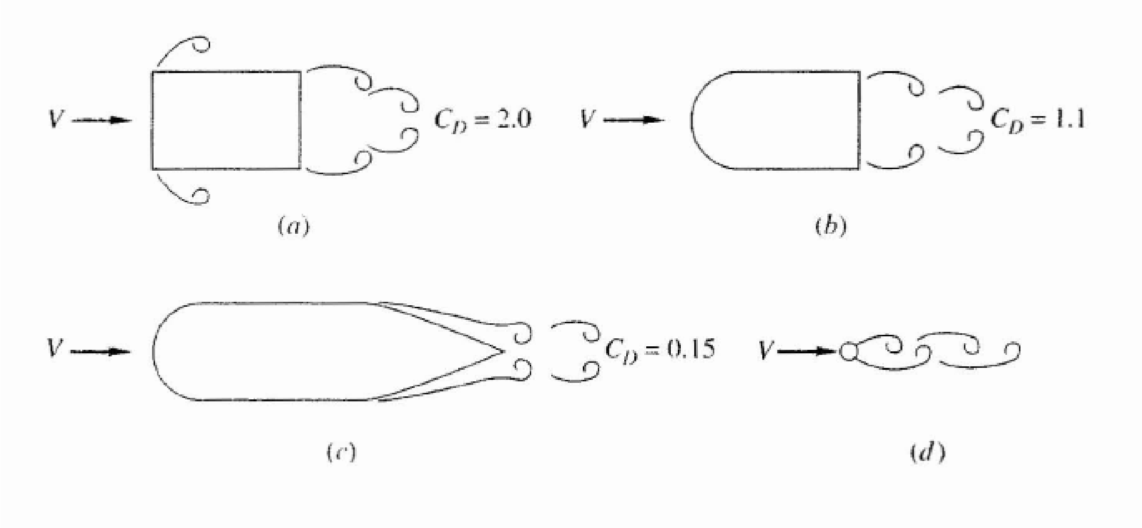

Figure 16. Drag Coefficient dependent on shape (From Ref 10)

The following sections of the report will provide a starting point for the conceptual design stage of the bow and stern units for the ASCC delivery system, which will aid in re-determining displacement, draft, and static stability of the vessel [8]. It is evident from Figure 14 and Figure 15 that the bow unit will have a slightly greater impact on the total drag resistance coefficient as compared to the stern unit. The subsequent designs, five NSWC Carderock Division bow unit and four NSWC Carderock Division stern unit designs, as well as an AEPCO bow unit design are merely starting points and purely conceptual. These concepts will be utilized as the initiating point for the design spiral for optimizing bow and stern shapes.

a. Bow One

Bows 1 through 5 were all concepts developed by NSWC Carderock Division. Bow 1 (B1) is a flat-plate (of height 8 feet when raised) that attaches to the front of the container and folds down to a 45º angle with side units that lock and hold it in place [8].

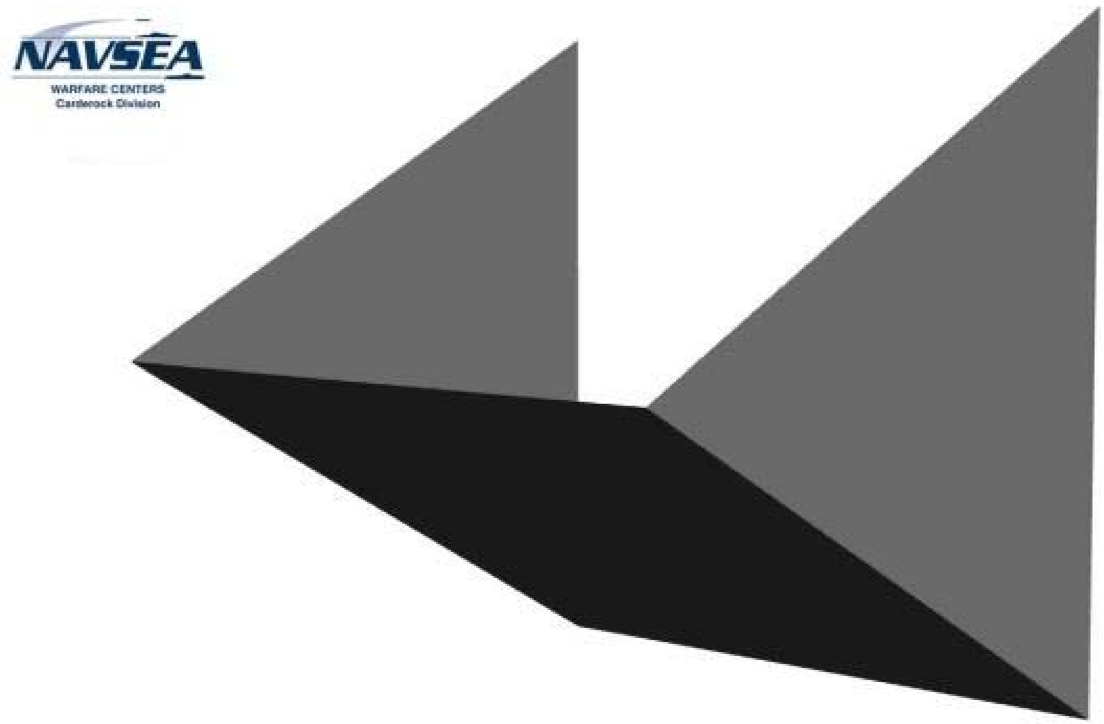

Figure 17. Bow 1 Plate Down (From Ref 8)

b. Bow 2

Bow 2 (B2) is the same flat-plate, except it folds down and locks in place at a 60^{o} angle to the horizon as compared to Bow 1's 45^{o} [8].

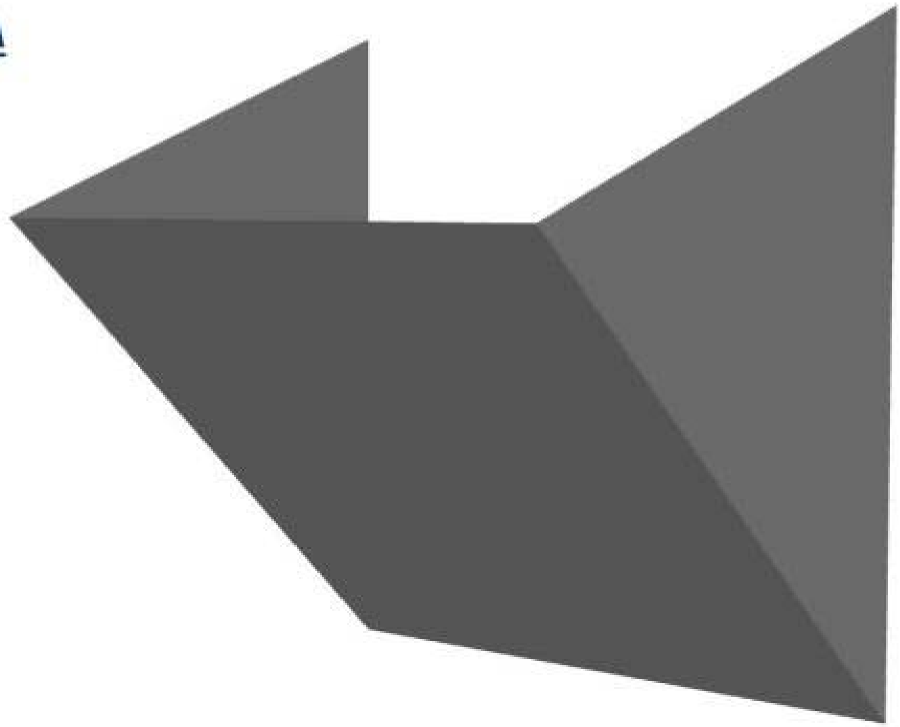

Figure 18. Bow 2 Plate Raised (From Ref 8)

c. Bow 3

Bow 3 (B3) below has an elliptical centerline, but comes to sharp points on the edges between the front of the bow unit and container edge [8].

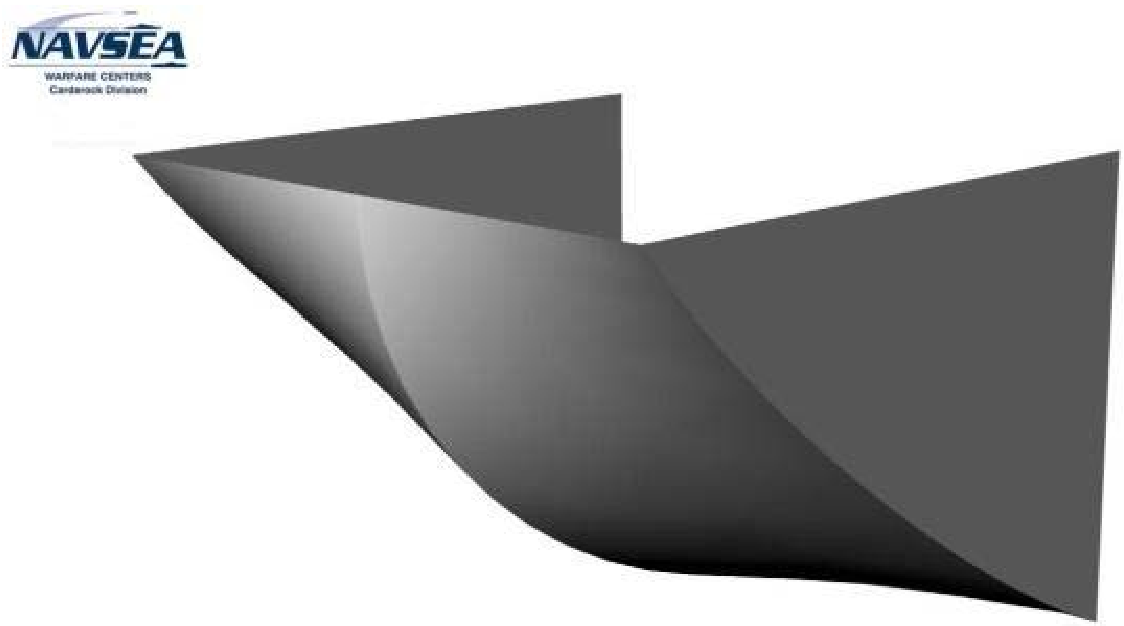

Figure 19. Bow 3 Elliptical Centerline (From Ref 8)

d. Bow 4

Bow 4 (B4) has an elliptical cross-section on the top and down the centerline [8]. This design was developed with the idea that an inflatable bow would give it its shape. It attaches to the edges of the container with a tight seal like the rest of the designs [8].

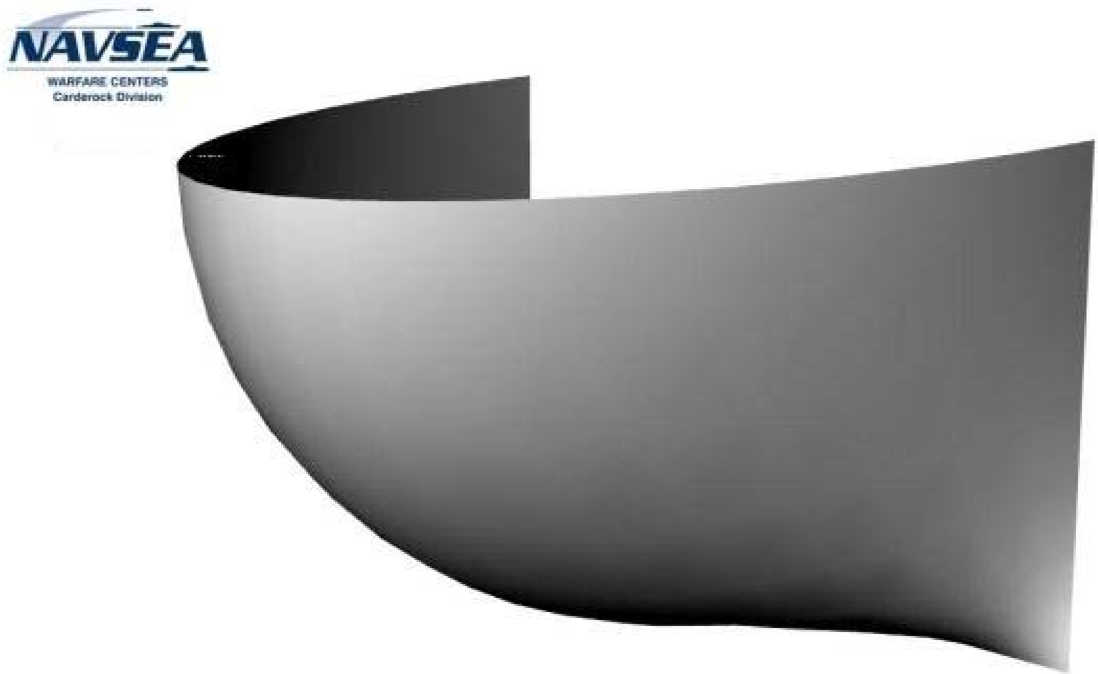

Figure 20. Bow 4 Inflatable with Elliptical Characteristics (From Ref 8)

e. Bow 5

Bow 5 (B5) is a combination of the middle designs in that it has some elliptical shape at the top, a hard chine line down the centerline, and somewhat flat edges along the sides [8].

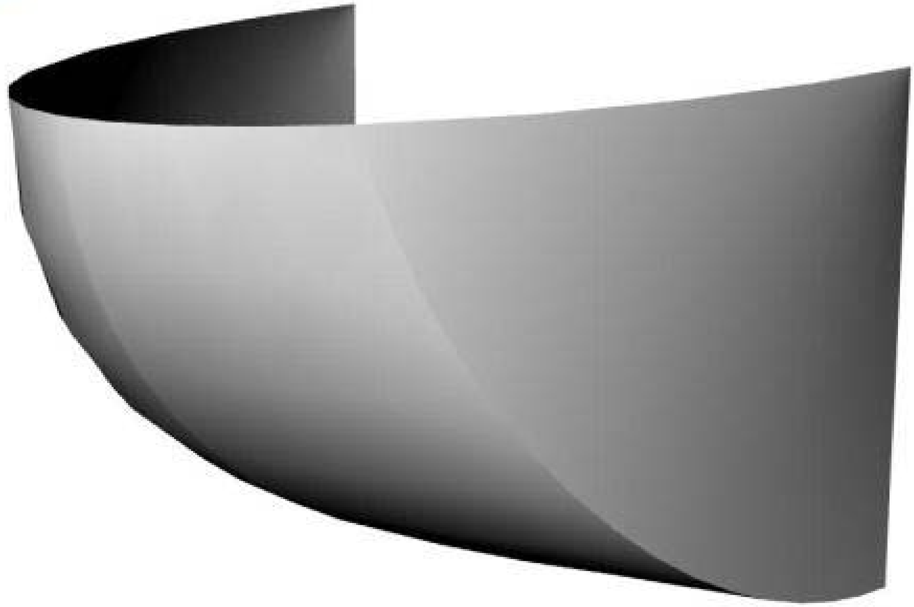

Figure 21. Bow 5 Mix of Rigid and Inflatable Bow (From Ref 8)

f. Bow AEPCO

Bow AEPCO is a conceptual design that created by AEPCO, Inc. It is the ballast assembly (bow unit) that was envision when the ASCC system was conceived.

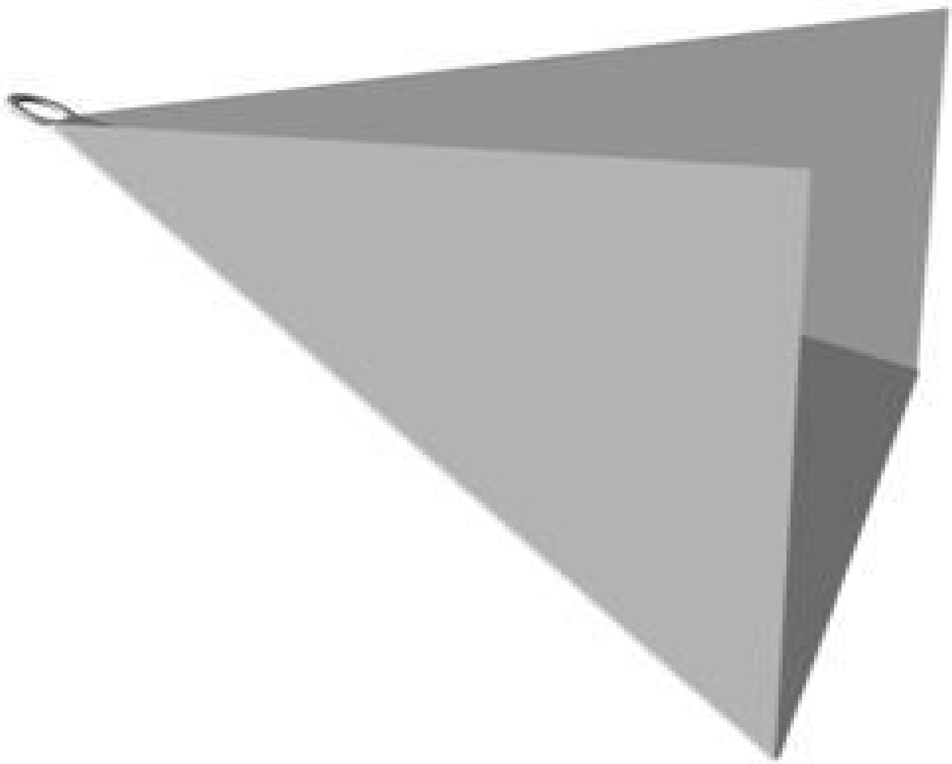

Figure 22. Bow AEPCO (From Ref 8)

2. Stern Units

The clear distinction between differing stern designs is the shape of the transom [8]. All stern concepts use the full eight feet length criteria [8]. The variations include changing the height and width of the semi-elliptical transom [8]. Stern 1 (S1), Stern 2 (S2), Stern 3 (S3), and Stern 4 (S4) are all initial design concepts that are subject to change depending on the findings of the propulsion group

a. Stern 1

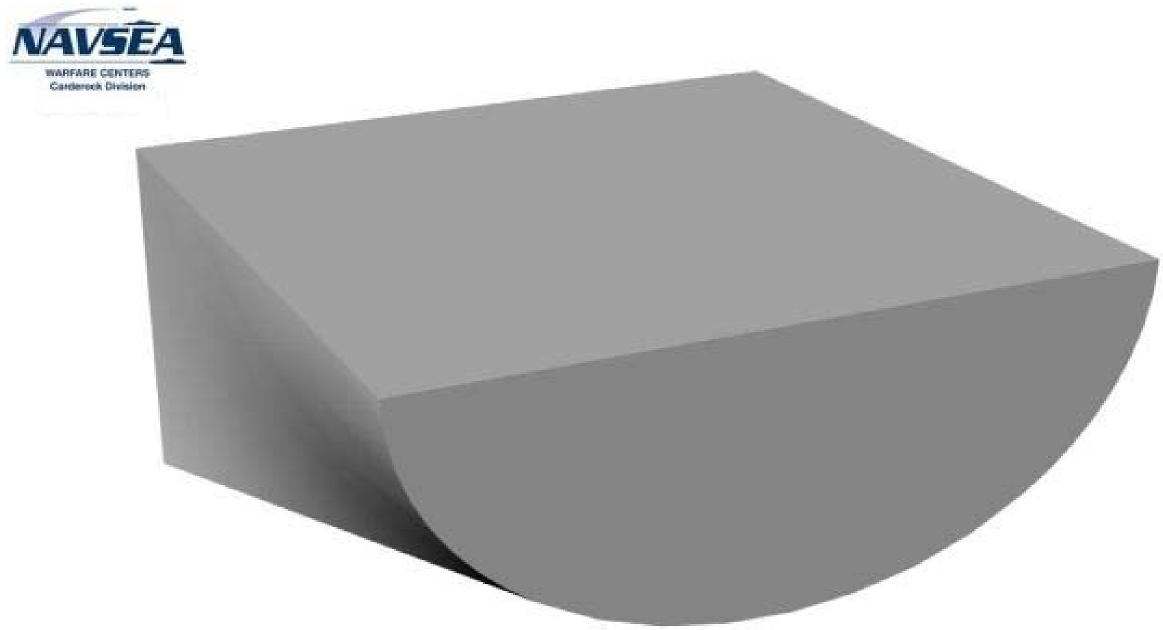

Figure 23. Stern 1 (From Ref 8)

b. Stern 2

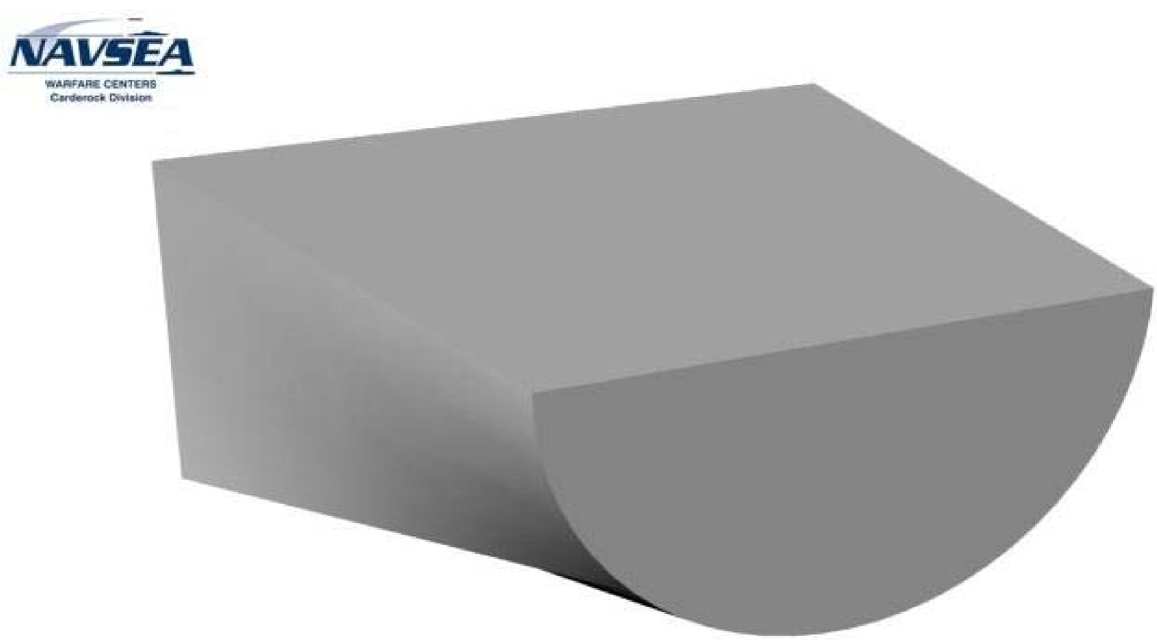

Figure 24. Stern 2 (From Ref 8)

c. Stern 3

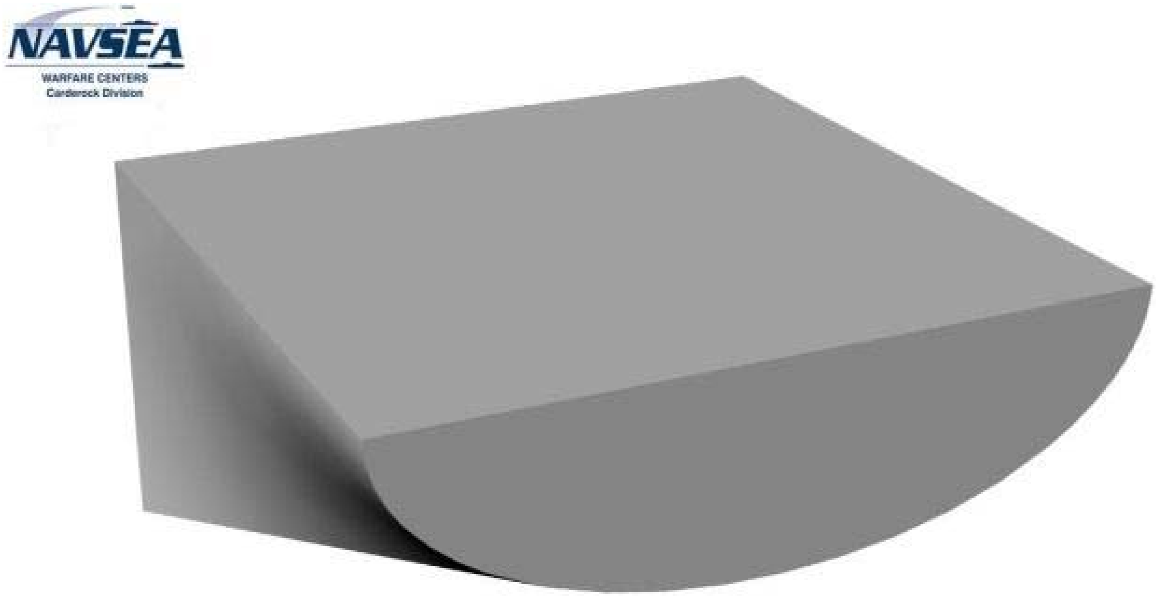

Figure 25. Stern 3 (From Ref 8)

d. Stern 4

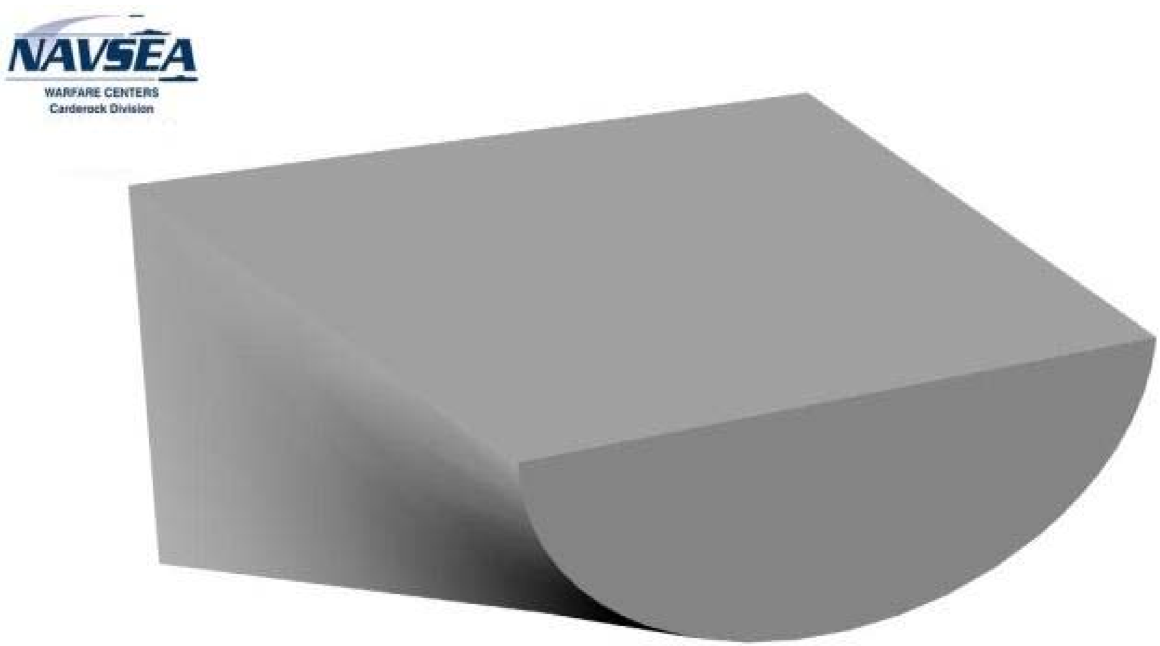

Figure 26. Stern 4 (From Ref 8)

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IV. RESISTANCE ANALYSIS

A. RESISTANCE THEORY

The resistance of a ship through water is caused by numerous fluid flow phenomena and is known as its required force needed to move that ship through a liquid medium at a given speed. The total resistance of a ship is made up of five main components; frictional resistance, wave-making resistance, flow turbulence resistance, form resistance, and air resistance [1]. Viscous resistance is broken down and categorized into frictional resistance and form drag. Wave-making, air, and flow turbulence resistance make up the other residual resistance categories. Equations of how the drag coefficient, Froude number, total resistance coefficient, and etc. were calculated are shown below with definitions of the variables followed.

$$C_d = \frac{F_d}{\frac{1}{2}\rho V^2 A} \tag{1.1}$$

F_d = total drag force
V = velocity of vessel
ρ = density of the fluid
A = planform area

$$Fn = \frac{V}{\sqrt{gL}} \tag{1.2}$$

Fn = Froude number
V = velocity of vessel
g = gravity
L = length

$$C_T = \frac{R_T}{\frac{1}{2}\rho V^2 S} \tag{1.3}$$

C_T = total resistance coefficient
R_T = total resistance on vessel
ρ = density of fluid which object is in
V = velocity of vessel
S = total wetted surface area of vessel

The total coefficient of resistance is the sum of the five main resistance coefficients.

$$C_{\text{Total}} = C_{\text{friction}} + C_{\text{wave}} + C_{\text{turbulence}} + C_{\text{form}} + C_{\text{air}} \qquad (1.4)$$

The following sections discuss resistance and each components effect of a body in motion through water.

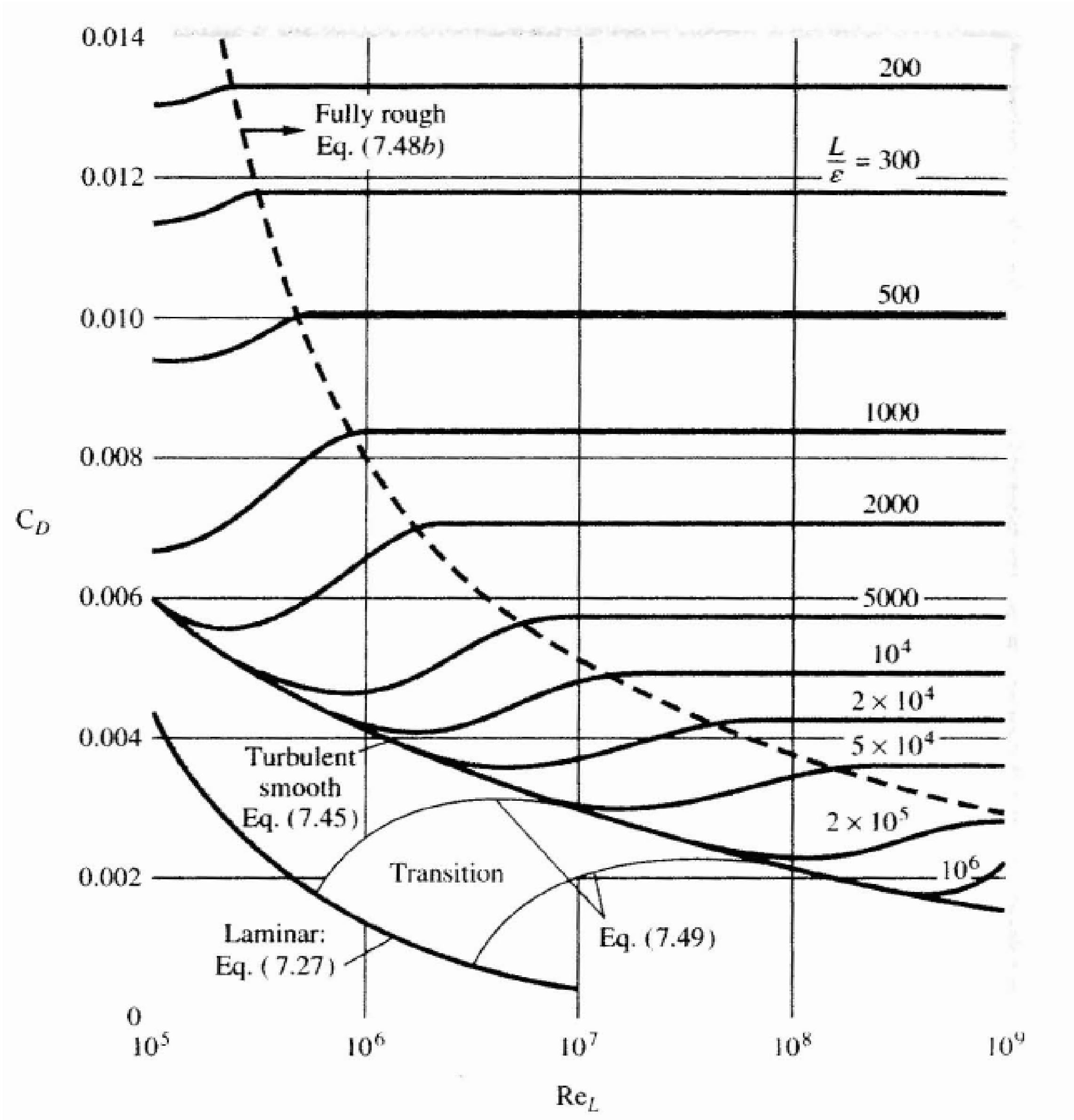

Figure 27. Reynolds number versus Drag Coefficient (From Ref 10)

1. Viscous Resistance

a. Frictional Resistance

Frictional resistance, which results from the fact that a solid surface (the ship's hull) moving through a viscous fluid carries with it some of the fluid immediately

adjacent to the hull within a region called the boundary layer [1]. Most of the theory governing frictional resistance promulgate from Froude's smooth plank experiments on friction [2].

$$R_F = f S V^n \tag{1.5}$$

R_F = frictional resistance (N)
f = friction coefficient
S = total wetted surface area (m^2)
V = velocity (m/s)
n = exponent of the speed

The most commonly used formulation for frictional resistance is the ITTC 1957 Line and is generally agreed as adequate for initial estimations of resistance [1]. Use of the ITTC line requires correlation allowance which is shown in the following table.

$$C_F = \frac{0.075}{(\log_{10} \mathrm{Re} - 2)^2} + C_A \tag{1.6}$$

C_F = resistance coefficient
Re = Reynolds number

Ship length on waterline		**Correlation allowance**
Meters	Feet	C_A
50-150	160-490	$+0.40\text{x}10^{-3}$
150-210	490-690	$+0.20\text{x}10^{-3}$
210-260	690-850	$+0.10\text{x}10^{-3}$
260-300	850-980	0
300-350	980-1,150	$-0.10\text{x}10^{-3}$
350-450	1,150-1,480	$-0.25\text{x}10^{-3}$

Table 4. Correlation Allowance with ITTC line (From Ref 1)

b. Form Resistance

Form resistance (form drag) is the portion of the resisting force encountered by a surface body moving through a fluid that is due to the irregularity of its

body shape and is directly due to shear stress. The layer of separation that occurs from that of the body at its surface of potential flow pattern is known as the boundary layer. Since the pressure and velocity changes and the extra path length are greater the fuller and stumpier the form, such shapes would be expected to have greater drag form [2]. This force is usually reducible to a minimum by streamlining the surface body. As an example, take the stern of a ship, if the curvature in the area becomes too abrupt, the water will no longer follow the shape of the hull and inevitably separates. Separation of this kind affects the overall pressure distribution of the hull and therefore introduces discontinuities into the streamlines of the flow [6]. Form drag is derived from the formation of the boundary layer and flow separation. The figure below is an illustration of the boundary layer along the surface of a body.

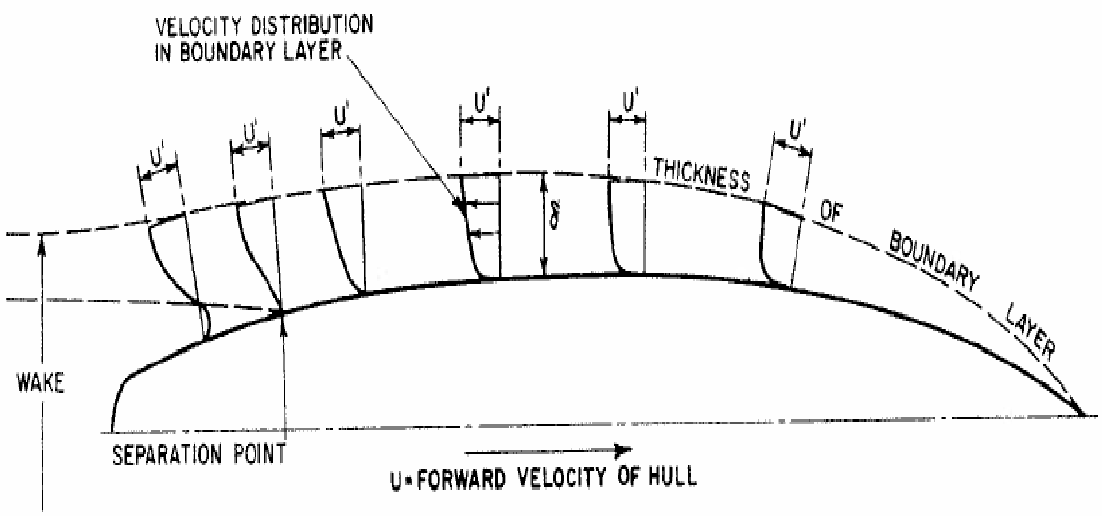

Figure 28. Boundary Layer Separation (From Ref 2)

From the definition of form drag, it was stated that the resistance is due to shear stress. Taking shear stress into account and taking into the theory behind turbulent flow for flat plates, it has been proven that the profile is logarithmic. Assuming logarithmic law holds true across the boundary layer, it can be stated that the following equation holds true.

$$\frac{V}{u^*} \approx \frac{1}{k} \ln \frac{\delta u^*}{\nu} + B \tag{1.7}$$

$V =$ velocity of fluid

$u^* =$ friction velocity

$\delta =$ displacement thickness

ν=kinematic velocity

$k = 0.41$

$B = 5.0$

$$u^* = \left(\frac{\tau_w}{\rho}\right)^{1/2} \tag{1.8}$$

$\tau_w =$ shear stress along wall

ρ=density of fluid

As the shear stress occurs along the hull, the skin friction coefficient, C_f, becomes prevalent and is analogous to the friction factor.

$$C_f = \frac{2\tau_w}{\rho V^2} \tag{1.9}$$

$$C_f = \frac{0.73}{\mathrm{Re}_x^{1/2}} \tag{1.10}$$

For a turbulent flat plate, a complex log friction law exists.

$$\left(\frac{2}{C_f}\right)^{1/2} \approx 2.44\ln\left[\mathrm{Re}\left(\frac{C_f}{2}\right)^{1/2}\right] + 5.0 \tag{1.11}$$

Some values of Reynolds number and friction coefficient are in the below table.

Re	10^5	10^6	10^7	10^8	10^9	10^{10}
C_f	0.00315	0.00217	0.00157	0.00120	0.00094	0.00075

Table 5. Form Drag based of Turbulent Boundary Theory

Turbulent boundary flow theory is one that is very complex and has been relegated to predominantly model testing. The complexity has produced numerous approximations and very few finite answers. The accepted method for predicting ship resistance is from a model that is based on the Froude assumptions where total resistance

is divided into frictional and residuary resistance [1]. Turbulent flow has always been assumed for all cases. If laminar flow is present during the ship model tests or plank tests, the expansion of the test results to full scale would not be correct [1].

2. Wave-making Resistance

The system of waves produced from the net fore and aft force upon the ship due to the fluid pressures acting normally on all parts of the hull is better known as the wave-making resistance [2]. Lord Kelvin first introduced the theory of wave-making resistance. He formulated that from a single pressure point travelling in a straight line over the surface of the water, sends out waves which combines to form a characteristic pattern [2]. These systems of transverse waves are divergent and that they originated from a single point. The pattern is contained from two straight lines starting from a pressure point and make angles of 19 degrees and 28 minutes on each side of the line of motion [2]. A diagram of Lord Kelvin's wave pattern is show below.

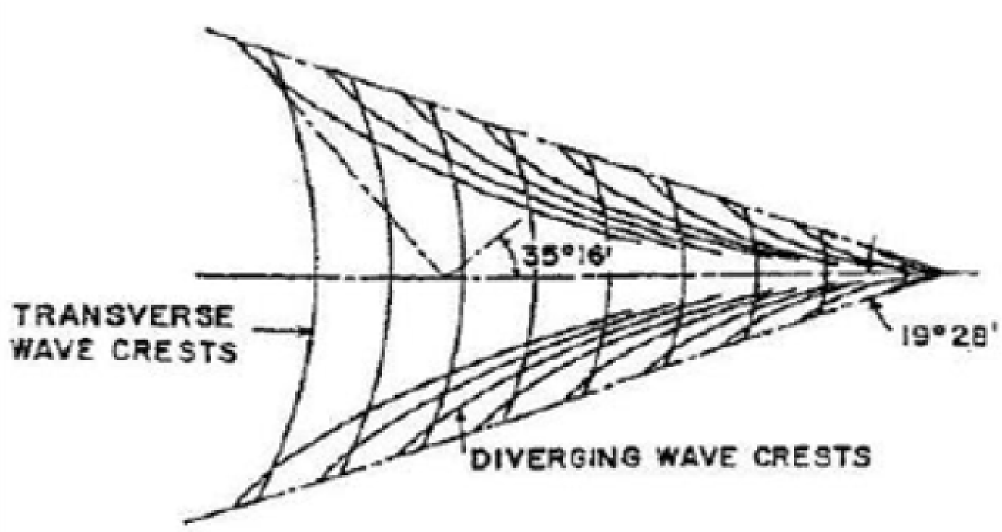

Figure 29. Kelvin Wave Pattern (From Ref 2)

The diagram above indicates that near the bow divergent waves exists. Between the divergent waves on each side of the ship, transverse waves are formed from their crest lines normal to the direction of motion near the hull, bending back as they approach the divergent-system waves and finally coalescing with them [2].

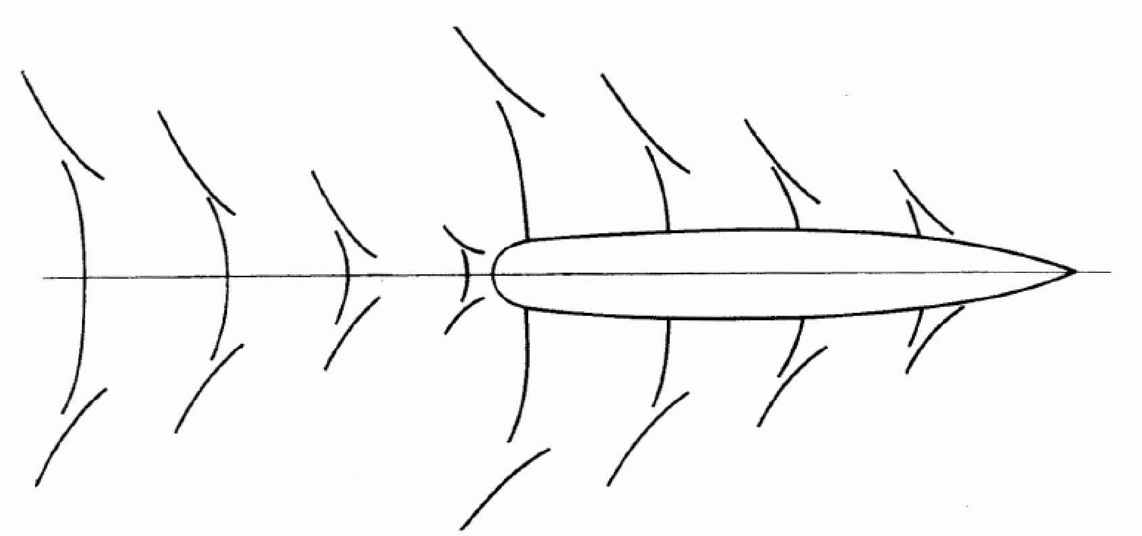

Figure 30. Schematic of bow and stern wave system (From Ref 2)

Additionally, as the speed of the ship increases, the wave pattern must change, for the length of the waves will increase and the relative positions of the crests and troughs will alter [2].

$$C_w = \frac{R_w}{\frac{1}{2}\rho S V^2} \tag{1.12}$$

C_w = coefficient of wave-making resistance

R_w = wave-making resistance

3. Air and Wind

Air and wind resistance is based upon the ship's speed and area and shape of the superstructure of the ship. A ship sailing on a smooth area and in still air experiences a resistance due to the movement of the above-water hull through the air [2].

Determining the resistance of a surface ship is a more complex problem than that of most other vehicles involving the flow of fluids because the surface ship moves through both water and air [1]. Due to this difficulty, naval architects usually estimate the still air resistance and simply add it to the hydrodynamic resistances when determining powering necessary. The actual calculations for air are usually evaluated

experimentally for differing geometries which usually involves not just the deckhouse but also the above deck equipment and gear.

$$R_{air} = C_{air}\left(\frac{1}{2}\rho_a A_{pt} V^2\right) \tag{1.13}$$

R_{air} = still air resistance

C_{air} = still air resistance coefficient

ρ_a = mass density of the air

A_{pt} = project transverse area of above water portion of the ship

V = ship speed

Due to the complexity to calculate still air resistance, average values are used and accepted to determine powering because of the small factor it has in comparison to other hydrodynamic resistances. A table of some sample coefficients is featured below.

Ship Type	C_{air} **Range**
General Cargo	0.60 to 0.85
Tanker	0.75 to 1.05
Container	0.60 to 0.75
Passenger	0.65 to 1.10
Combatant	0.40 to 0.80

Table 6. Still Air resistance Coefficients

It must be noted that the still air resistance coefficient define above is based on the density of air and the above-water transverse projected area of the ship and is not directly additive to the frictional and residuary resistance coefficients [1]. In order to directly additive, a more commonly used formulation for determining still air resistance is based on the underwater wetted surface area and density of water.

$$C_{AA} = \frac{R_{air}}{\frac{1}{2}\rho_w S V^2} \tag{1.14}$$

C_{AA} = different still air coefficient

ρ_w = density of seawater

S = underwater wetted surface area

V = ship speed

The relation between the above C_{AA} and C_{air} equations are as follows assuming standard equivalent inputs.

$$C_{AA} = C_{air}\left(\frac{\rho_a}{\rho_w}\right)\left(\frac{A_{pt}}{S}\right)$$
$$C_{AA} = 0.001194\left(\frac{A_{pt}}{S}\right)C_{air} \tag{1.15}$$

Wind resistance is much more difficult to calculate than that of still air because factors such as the strength of the wind and its direction play a significant role in the overall resistance. Wind is segregated into “true” and “apparent” or “relative” winds. True wind refers to the wind direction at a point above the sea independent of whether a vessel is there or not. Relative winds refer to the vectorial summation of the velocities and directions of the ship and true winds [2]. It is very difficult to determine the wind resistance not only because of the direction and strength of the wind but also because a realistic sea-surface wind velocity profile model is nearly impossible in a wind tunnel.

Resistance, whether it is frictional and/or residual, is extremely critical to when talking about throughput efficiency of the ASCC. However, the smoothest hull design will not necessarily produce the least resistance and best results. As seen in the figure below, the ball on the left (a) is completely smooth and the angle of separation is earlier, at about an 80^{o} angle. The ball on the right (b) has separation later, at about an angle of 120^{o} angle. Both balls are traveling through the water at a rate of 25 feet per second. The difference in separation of the balls are similar to that of a golf ball travelling through the air, as a ball without dimples will travel less in distance than a ball with dimples.

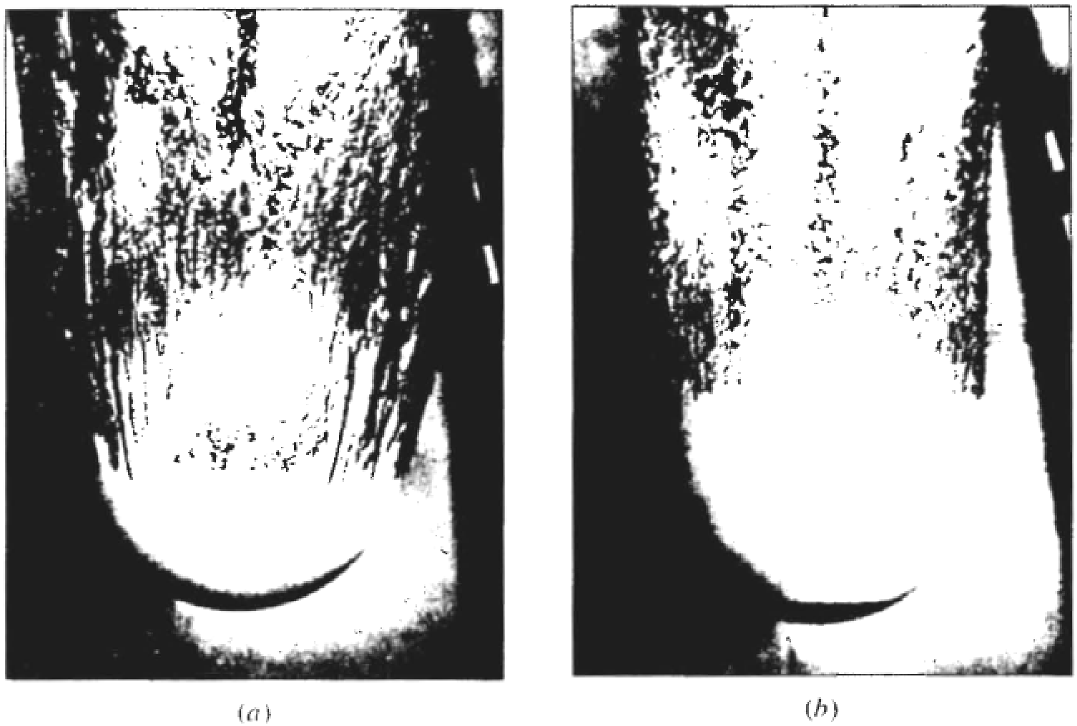

Figure 31. Smooth Ball vs Rough Ball (From Ref 10)

B. RESISTANCE OF BOW AND STERN UNITS

1. Bow Units

From Figures 14 and 15, it was determined that the bow unit would have a more prevalent impact on the drag resistance coefficient than that of the stern unit. The paper will look at the differing bow units first since they do have a bigger impact on the resistance.

a. Bow Unit Analysis

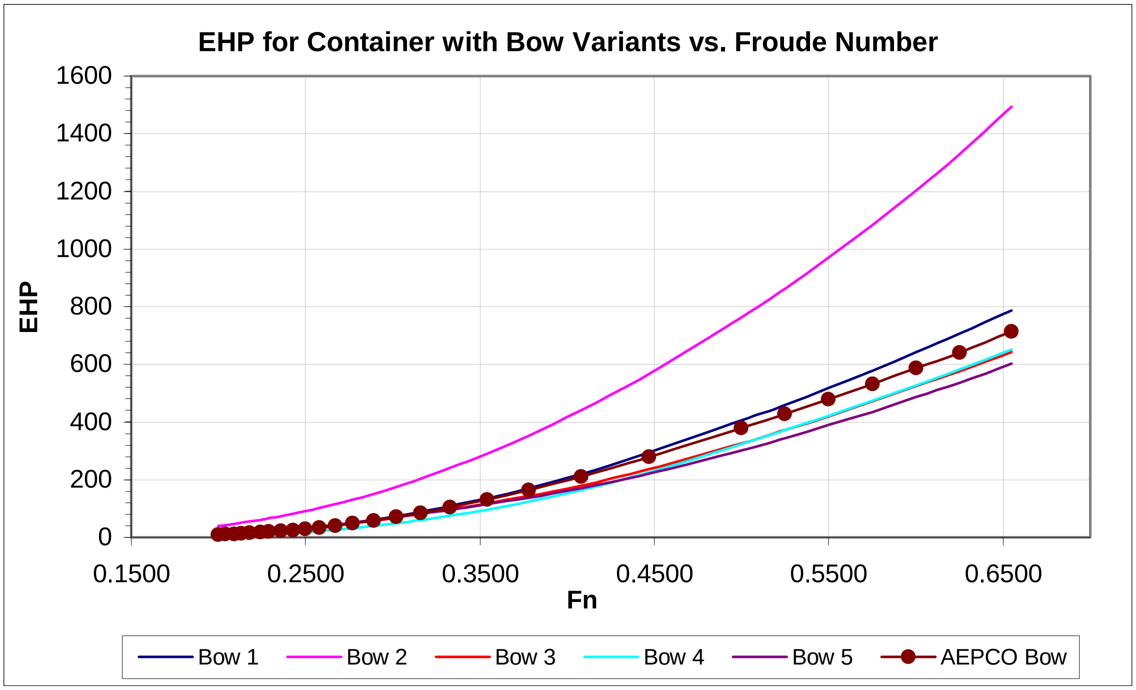

Figure 32. EHP vs Froude number for Bow variants

Recalling from the previous chapter of the various conceptual bow designs and as shown in the figure above, the trend is that when the design of the bow moves from a flat plate or surface to one that is more elliptical, the required horsepower is reduced. Of the conceptual bow designs applicable, Bow 5 produced the best results. Recalling Bow 5 was a combination of the inflated and rigid bow with elliptical characteristics, Figure 21. The rigidity and smoothness of the Bow 5 creates the necessary separation that produces the least amount of resistance through the water out of the six conceptual designs.

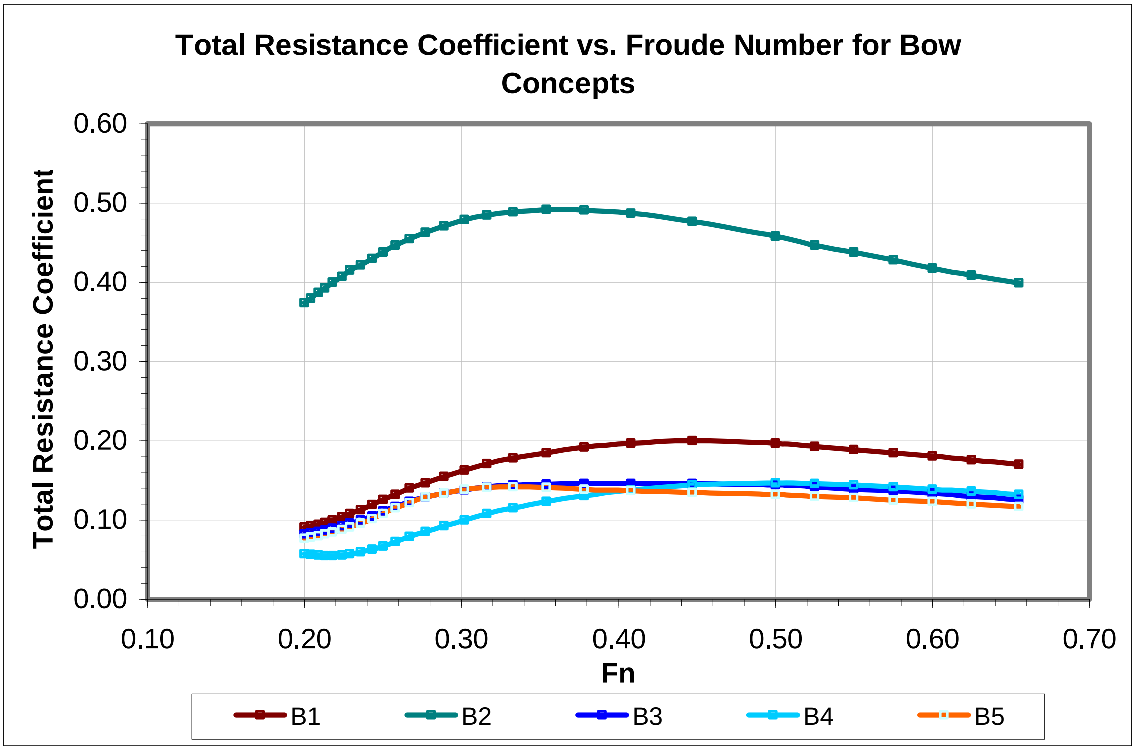

Figure 33. Total Resistance vs Froude number (From Ref 8)

The figure above is an illustration of the total resistance versus Froude number. To reinforce the analysis, the AEPCO bow was examined for three differing configurations. A study of bow door heights and their effects on resistance are shown below.

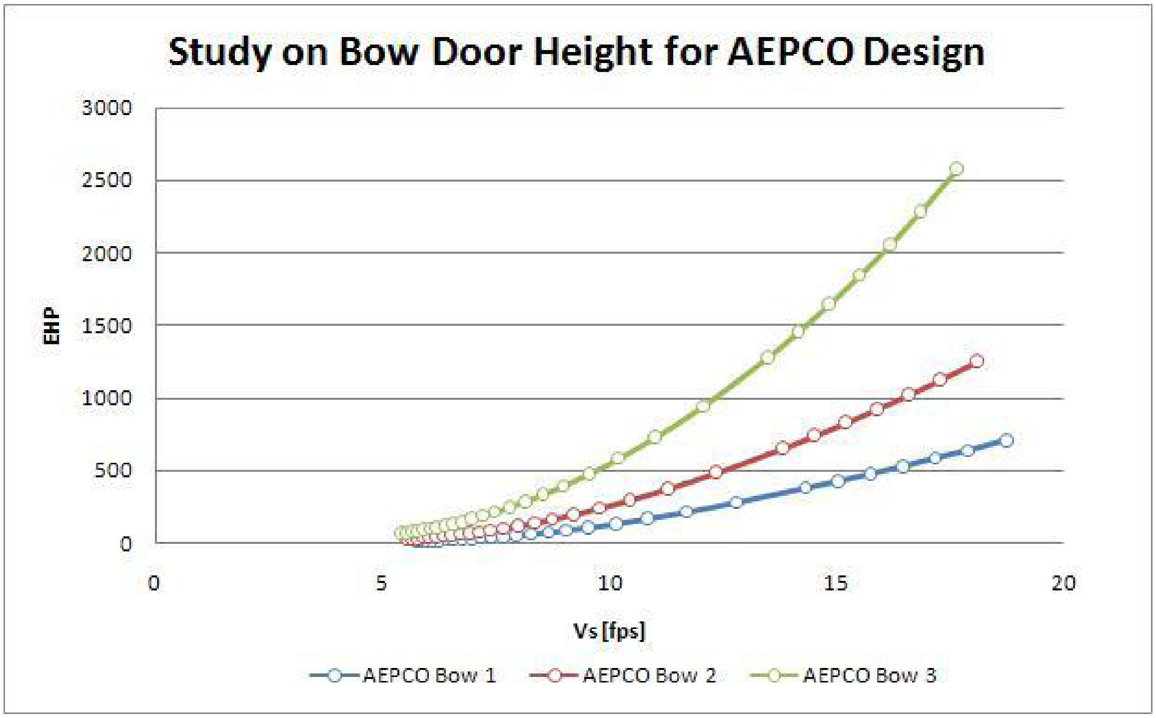

Figure 34. AEPCO Bow Door at various heights (From Ref 8)

The height in which bow door is fixated resulted in additional total drag resistance. AEPCO Bow 1 has the forward most point on the waterline [8]. AEPCO Bow 2 is raised 10 degrees (increase the bow rake, decrease the still waterline length) [8]. AEPCO Bow 3 is raised 20 degrees [8]. Analysis confirms the common sense notion that if one raises the bow, the drag is increased on the vessel; indications are that it is important to have some control on the vessel to ensure that the furthest bow point is located close to the waterline and not folded higher up on the vessel than necessary [8]. Essentially, AEPCO Bow 1 and the amount of surface area in the water along with its angle will have less total drag than that of AEPCO Bow 3.

b. Stern Unit Analysis

Stern units for the ASCC system are to be designed with a semi-elliptical transom. As previously stated, the transoms will be design limited to use a full eight feet length criterion with the only variations involving height and width.

Currently, there is insufficient data to make a selection of the best transom for the hull design. However, data will show that the need for a bow unit and stern unit to add to the ISO cargo container is of the utmost importance.

c. Bow Unit and Stern Unit Analysis

The below figure is just a sample replication of what an ISO cargo container would look like if it were combined with a bow unit and stern unit. The attached units are Bow 1 and Stern 1, respectively.

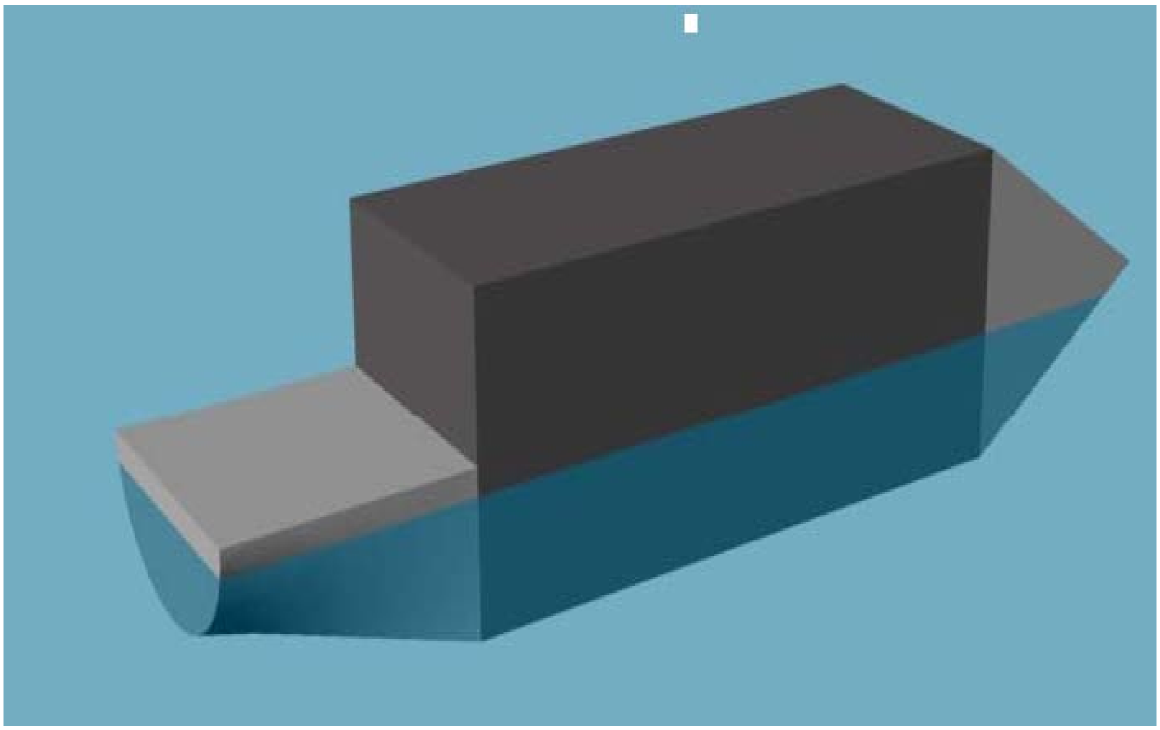

Figure 35. Bow unit and Stern unit on ISO Container (From Ref 8)

The combination of Bow 1 and Stern 1 are by far not the ideal choice as far as resistance and efficiency through the water are concerned. Data has shown that Bow 5 has the lowest resistance through water out of all the conceptual designs. Choosing a stern will be difficult without necessary data, however, the need for a stern unit is quite evident. The assumption will be taken that the differences in stern unit will be very minimal; therefore out of simplicity Stern 1 will be used.

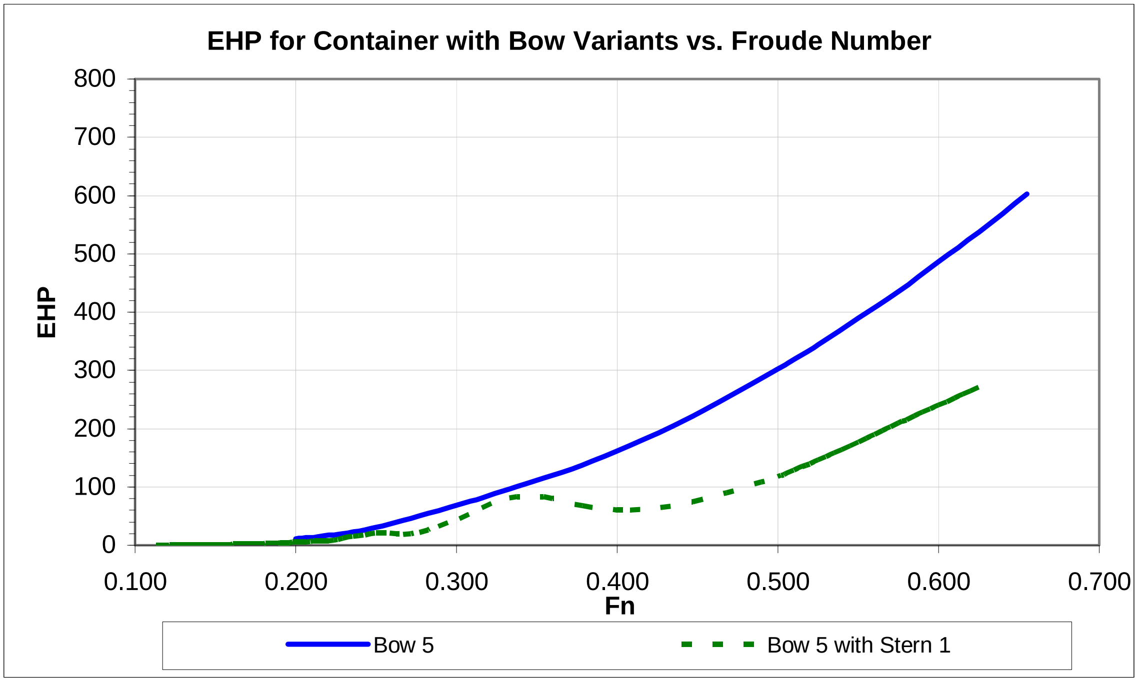

Figure 36. EHP vs Froude of Bow 5 and Stern 1 (From Ref 8)

As an example, Bow 5 which has a combination of inflatable and rigid shell with elliptical features was merged with Stern 1, was analyzed to show effective horsepower versus Froude number. The figure indicates that with the use of Stern 1 in combination with Bow 5 will reduce the total drag force of the cargo container by nearly 50% as compared to if the container had only Bow 5.

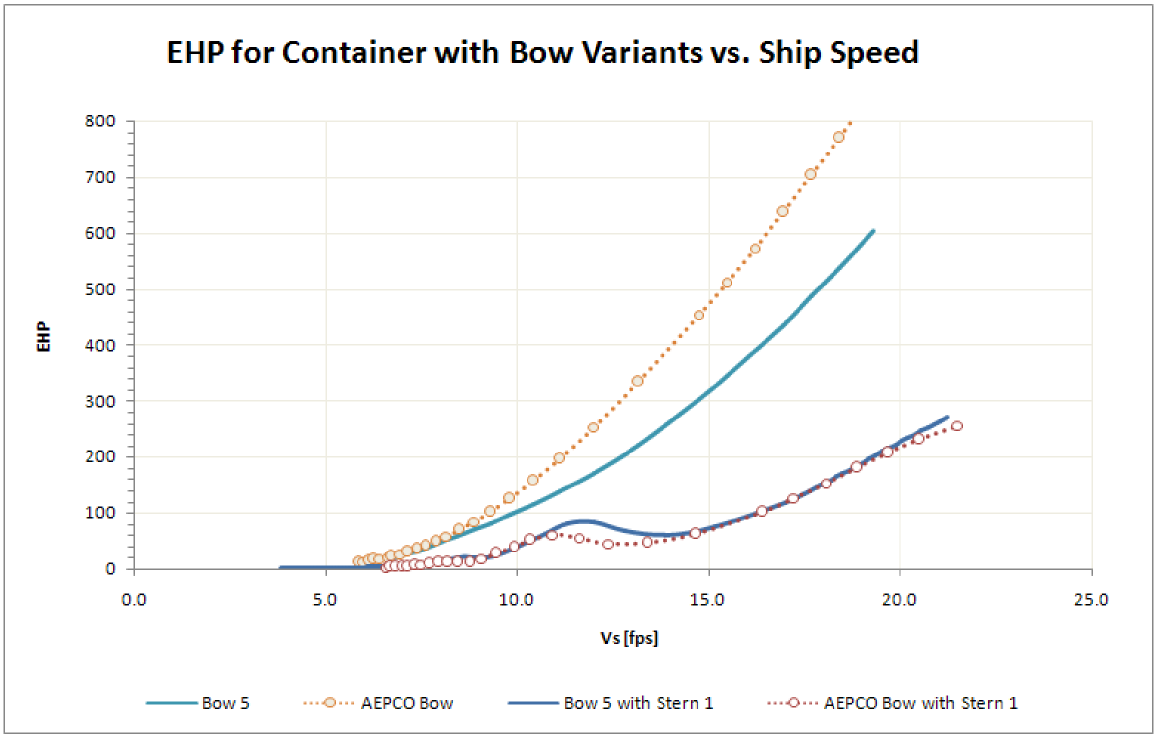

Figure 37. EHP vs Froude of Bow AEPCO and Stern 1 (From Ref 8)

After evaluating the bows, one Carderock bow and the AEPCO bow were reanalyzed with a stern unit attached to reiterate the positive effects of a stern in decreasing drag [8]. The best NSWC Carderock Division bow performance came from Bow 5. The previous figures have proved that the bow units are the components that will be most critical when referring to resistance through the water for the ASCC delivery system. Also concluded from the figures above, is that Bow 5 will have the least resistance through the water with all bow heights above the waterline being equal. The AEPCO bow was analyzed because it was the envisioned bow unit when concept was created. Thusly, Bow 5 with Stern 1 and the AEPCO bow with Stern 1 were compared against the bow only values [8].

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V. ANALYSIS OF THROUGHPUT EVALUATION

A. THROUGHPUT ANALYSIS

The previous chapter's discussions on resistance and its numerous subcomponents have clearly proven that resistance performs an integral function in the determination of throughput. The subsequent section will analyze the performance of throughput based on resistances due to the conceptual designs that were mentioned prior. Figure 38 was taken from the Resistance Analysis chapter and shows the Effective Horsepower (EHP) versus Froude number based on bow variants. The linear data was then taken for each bow variant and a trendline was provided. The trendline that produced the best results was a second order polynomial equation and each equation for their respective bow variant is shown on the figure.

Performance of each analyzed also with differing loading factors and speeds. Due to the fact that the actual propulsion system to be placed onto the ISO cargo container has not been selected, it was rather evident that several differing speeds for each needed to be tested and analyzed. It was also formulated that the need for varying loading capacities and specific fuel consumptions were necessary. For each bow variant a throughput analysis will be conducted with differing loads, specific fuel consumption, and speeds.

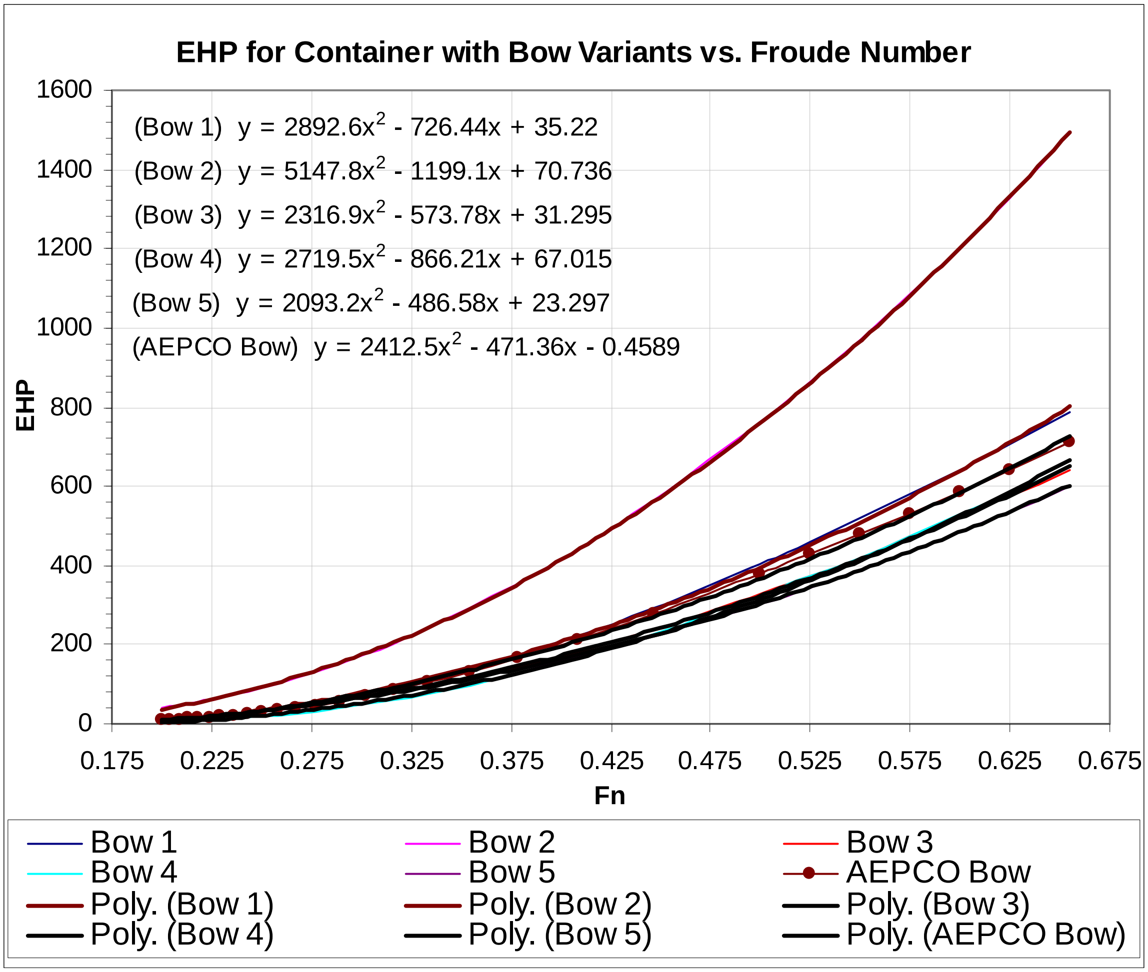

Figure 38. 2nd Order Polynomial Equations Trendlines for conceptual Bows

After the second order polynomial equations trendlines were produced, it becomes rather evident that Bow 5 will have the least resistance through the water.

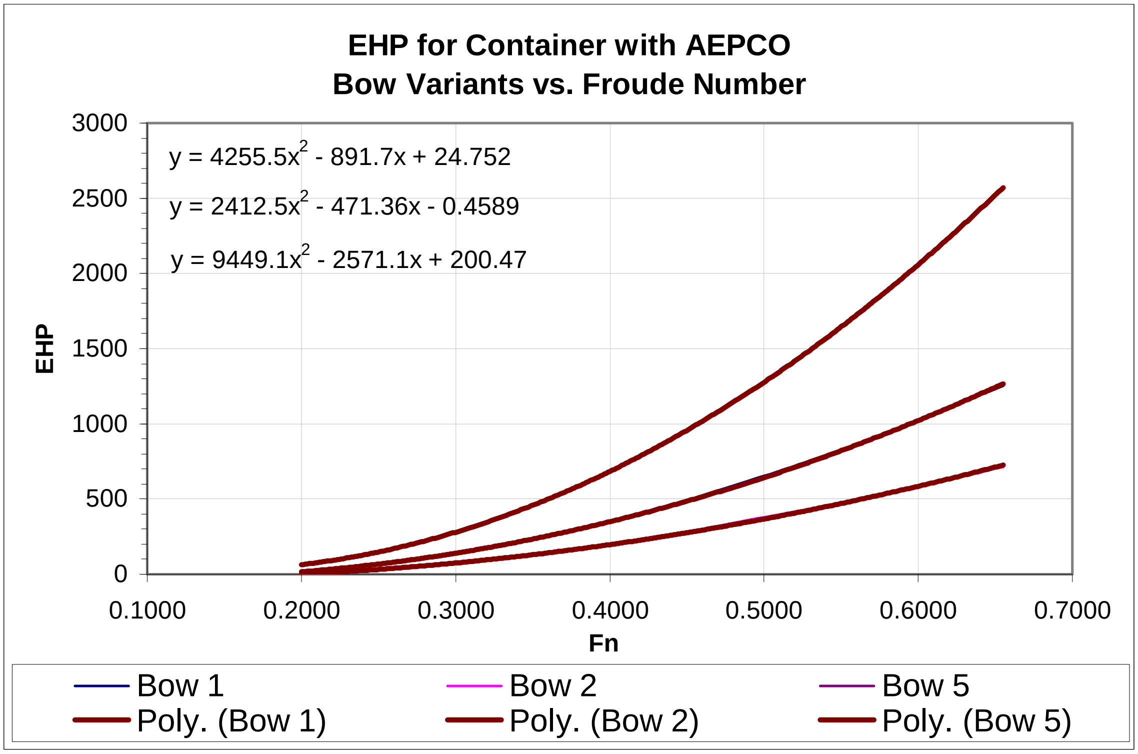

Figure 39. 2nd Order Polynomial Equations Trendlines for Bows with Variants

Figure 39 is a representation of the AEPCO Bows at differing door heights as discussed earlier. AEPCO Bow 5 has greater bow rake and less still waterline length meaning that it will have less resistance through the water.

However, the AEPCO bows do not produce less resistance than that of Bow 5. For this reason, the paper will focus on the throughput efficiency of Bow 5 with Stern 1 as the optimum combination of bow and stern units.

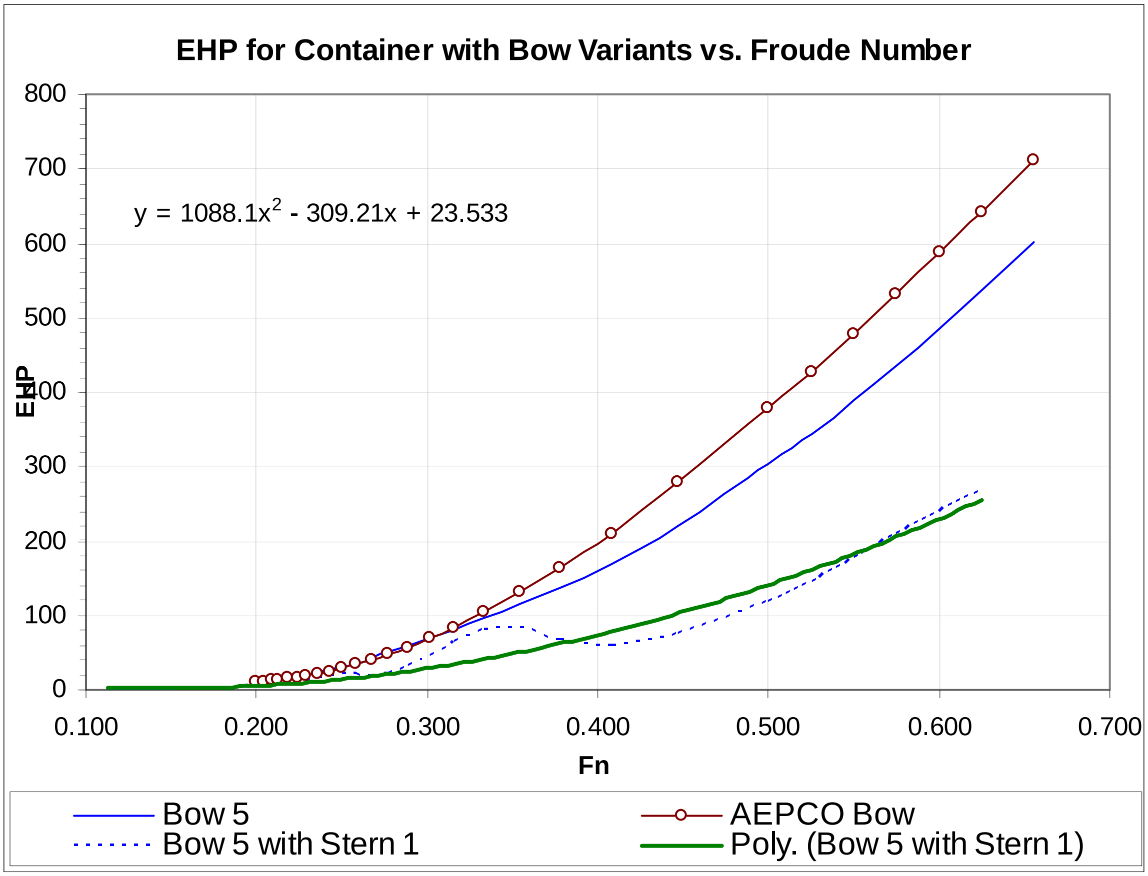

Figure 40. 2nd Order Polynomial Equation trendline for Bow 5 and Stern 1

With this in mind, the following data for throughput efficiency involves the use of Bow 5 and Stern 1. The above figure shows the trendline for the combination of Bow 5 and Stern 1. The data for the combined Bow 5 and Stern 1 configuration (configuration 6) was used in comparison to that of Bow 1 (configuration 1). It is rather obvious that Bow 1 definitely has greater resistance and less throughput efficiency. However, throughput can also be analyzed from a loading (percentage of total capacity of 20 feet ISO cargo container), range, and specific fuel perspective. The following figures show the normalized payload for different values of loading condition, range, and specific fuel consumption (SFC).

1. Bow 1 (Configuration 1)

There are several conclusions that can be drawn from the following figures.

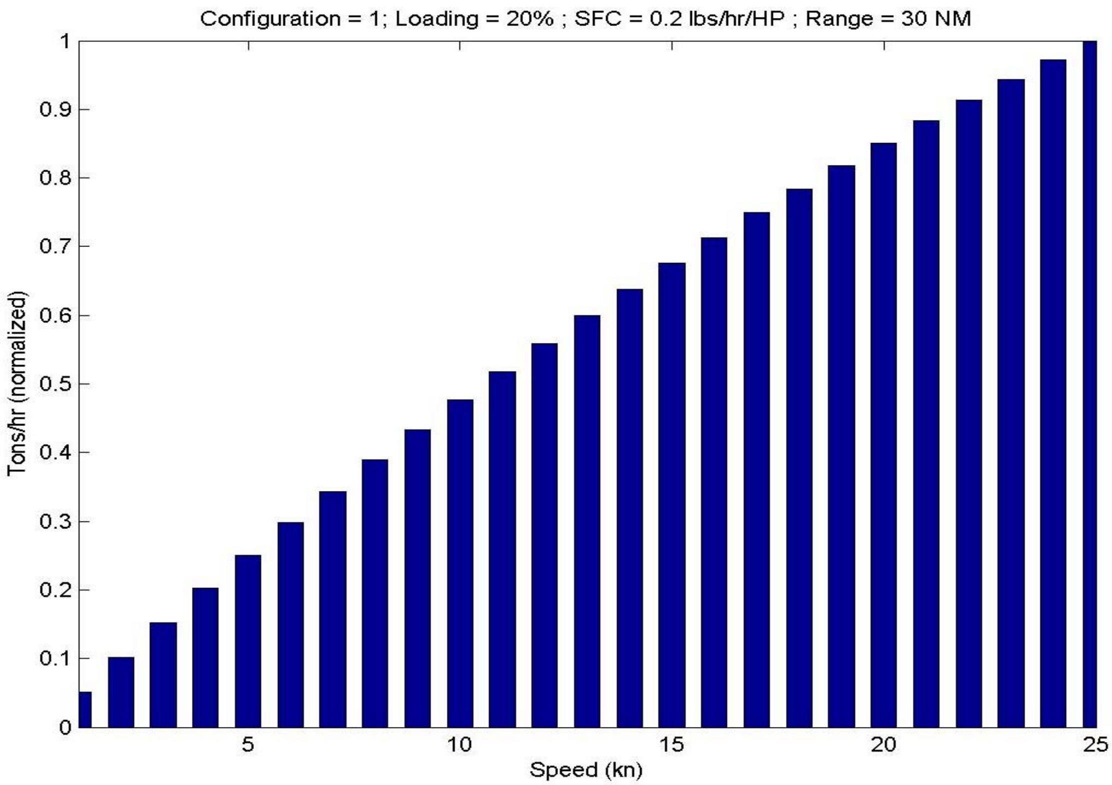

Figure 41. Tons/Hr vs Speed for Bow 1 (20%, 0.20, 30)

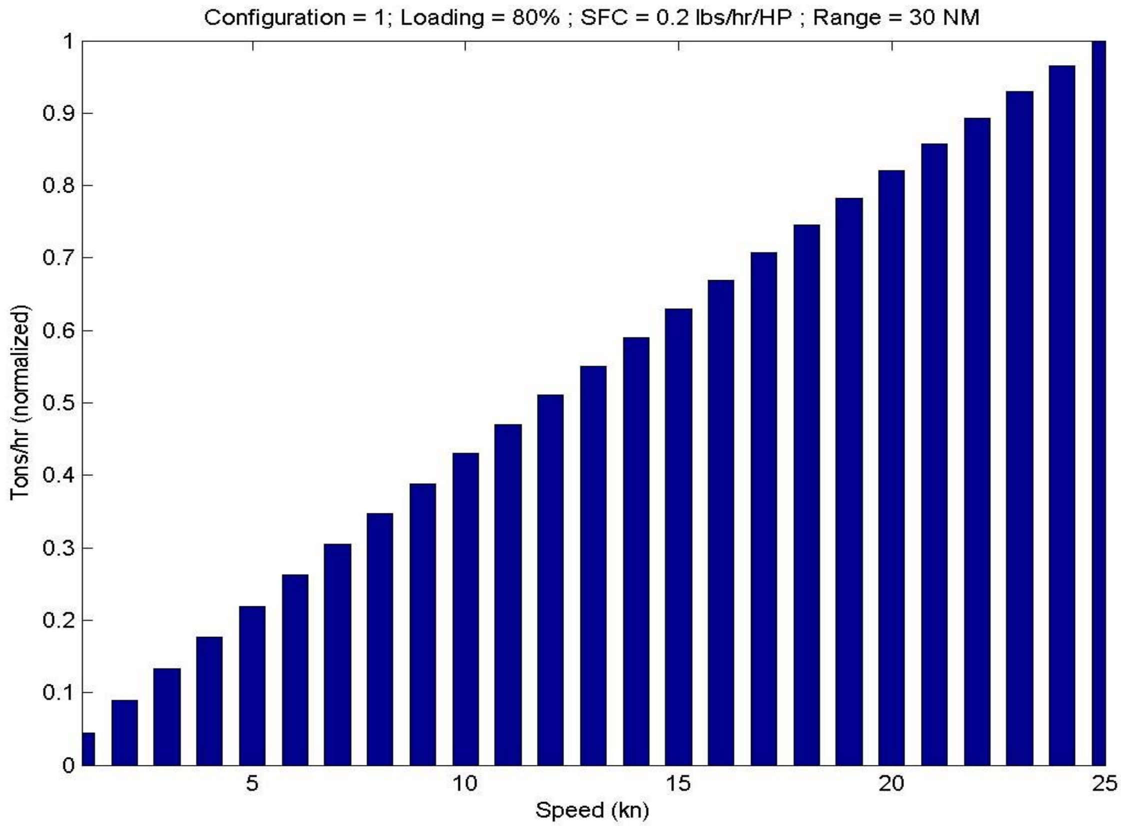

Figure 42. Tons/Hr vs Speed for Bow 1 (80%, 0.20, 30)

For low values of SFC and range, payload transfer is almost directly proportional to speed. This is especially true as the container loading fraction is increased. In this case, fuel consumption is a small part of the overall cargo transfer capability of the vehicle.

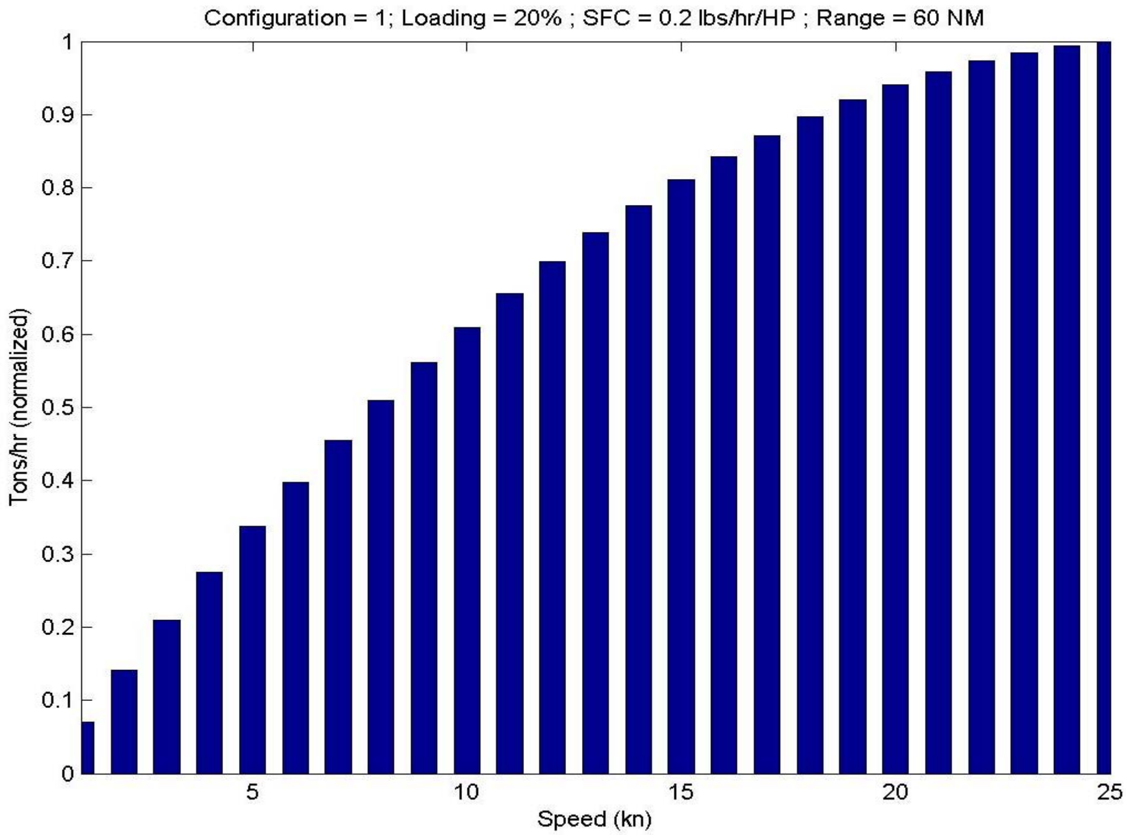

Figure 43. Tons/Hr vs Speed for Bow 1 (20%, 0.20, 60)

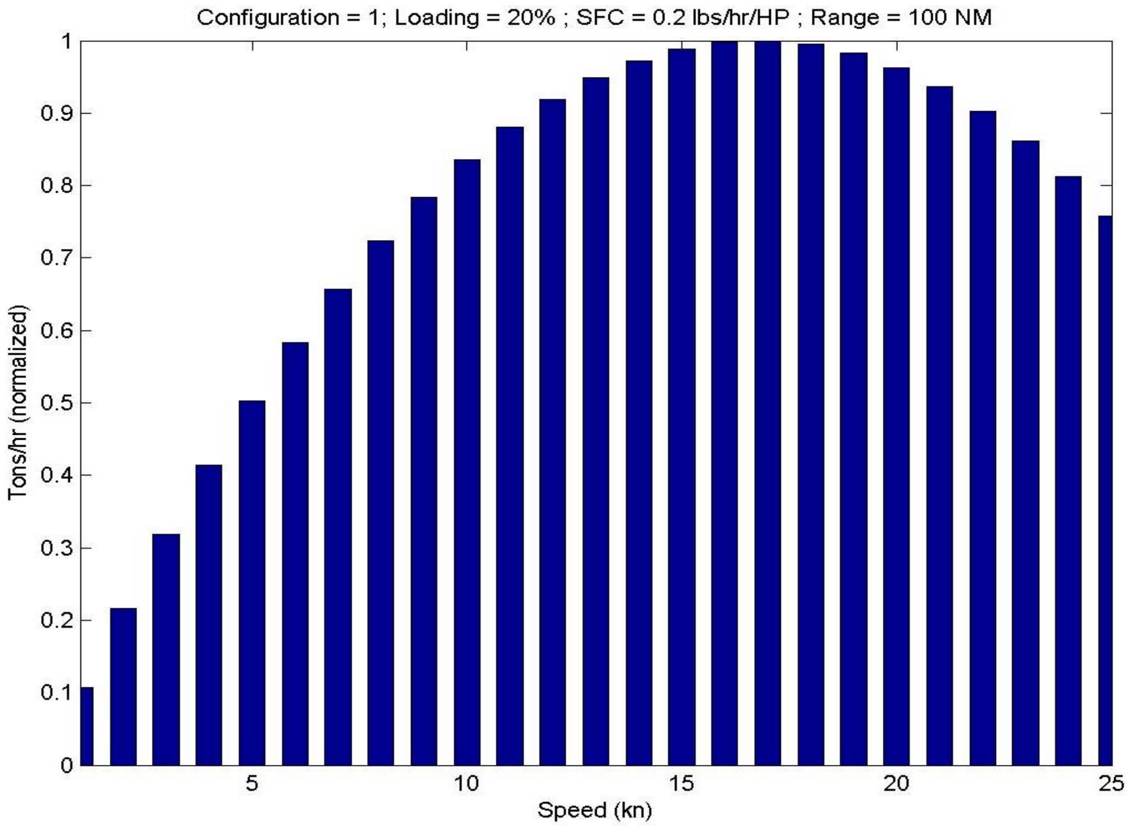

Figure 44. Tons/Hr vs Speed for Bow 1 (20%, 0.20, 100)

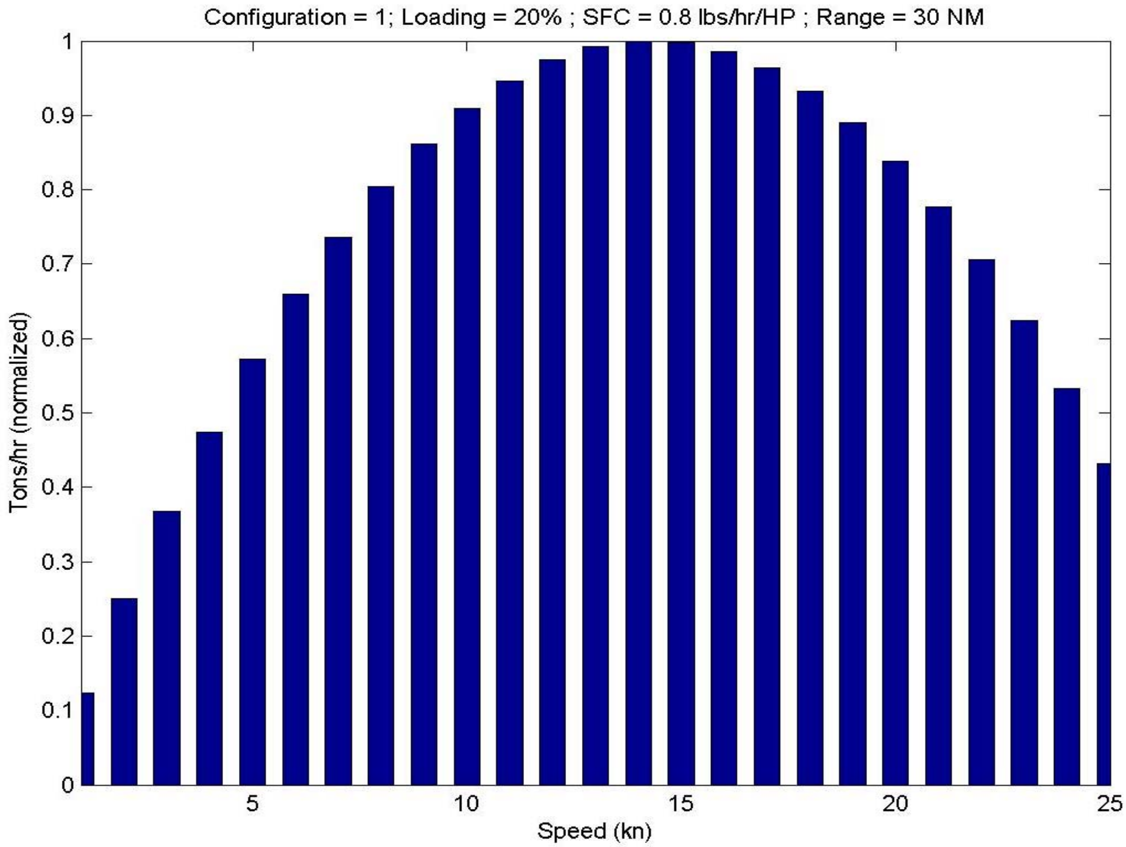

Figure 45. Tons/Hr vs Speed for Bow 1 (20%, 0.80, 30)

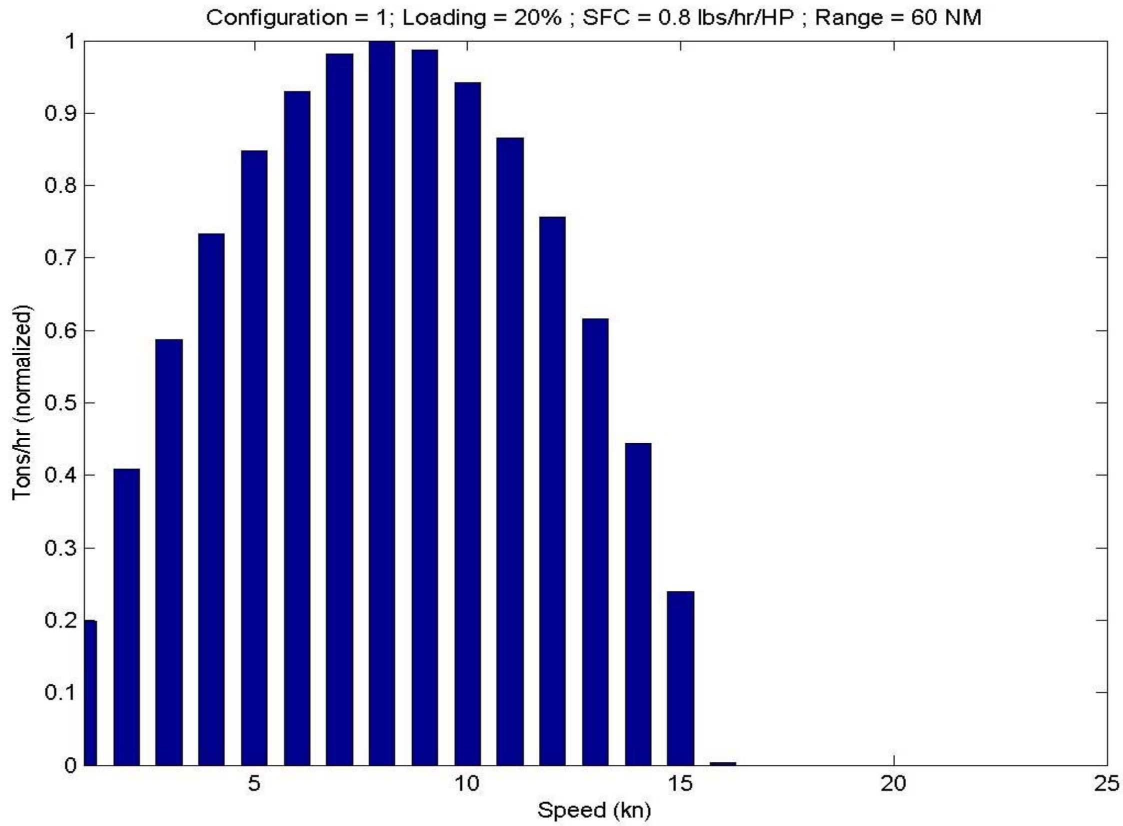

Figure 46. Tons/Hr vs Speed for Bow 1 (20%, 0.80, 60)

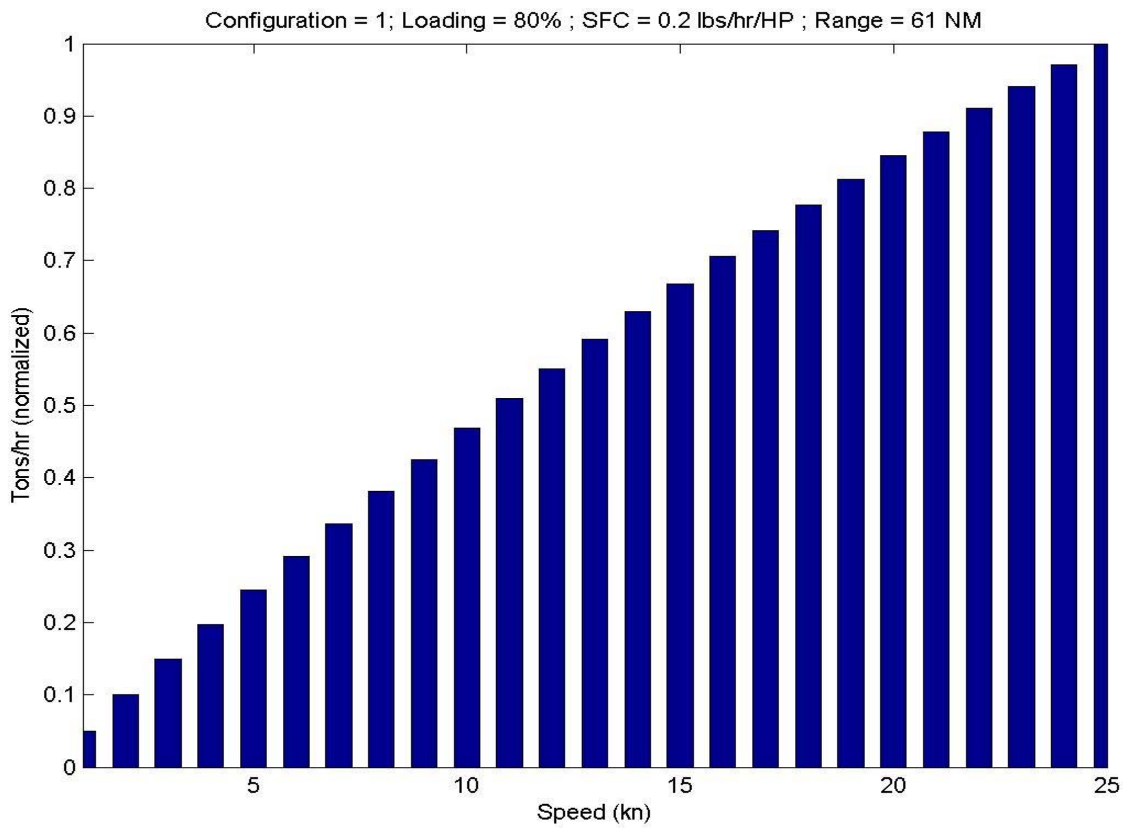

Figure 47. Tons/Hr vs Speed for Bow 1 (80%, 0.20, 61)

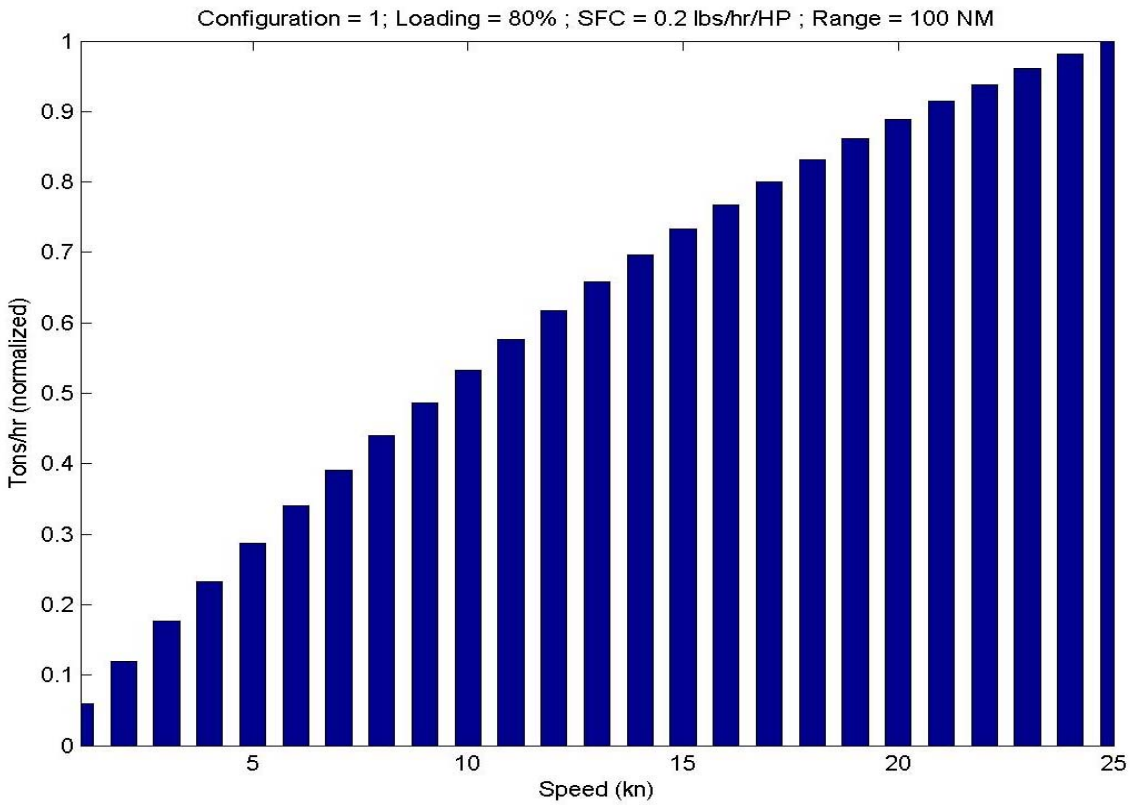

Figure 48. Tons/Hr vs Speed for Bow 1 (80%, 0.20,100)

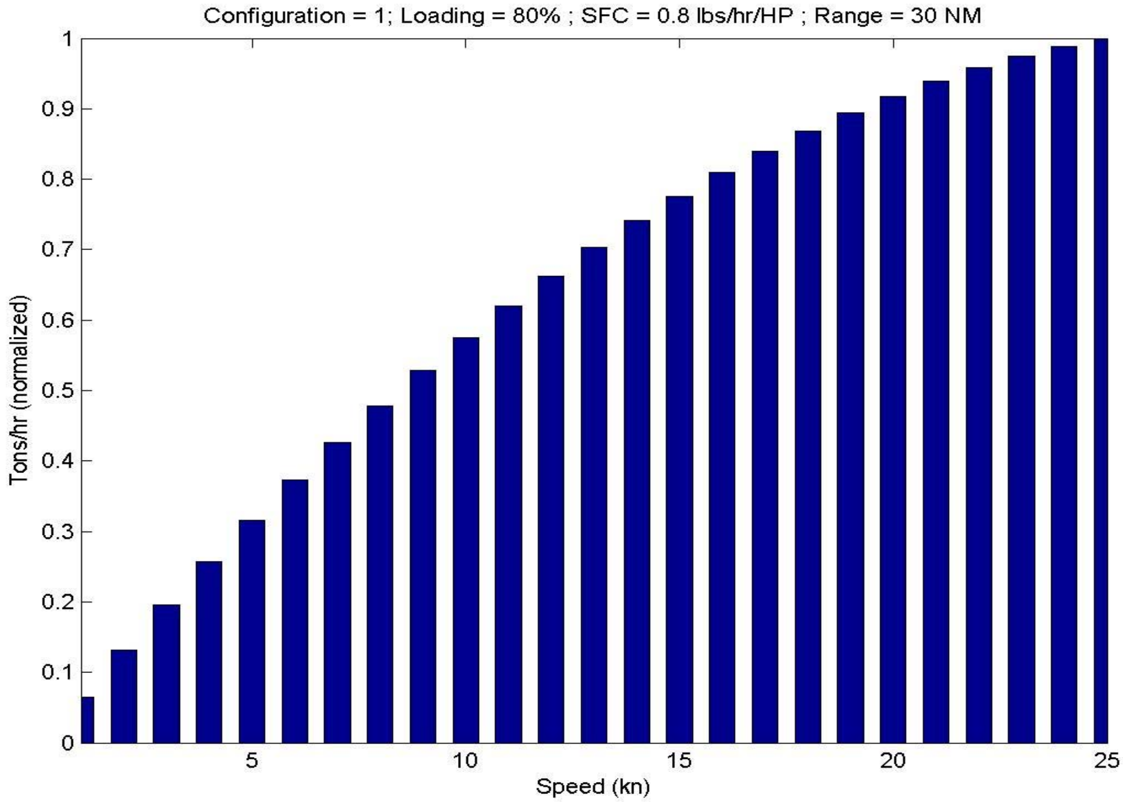

Figure 49. Tons/Hr vs Speed for Bow 1 (80%, 0.80, 30)

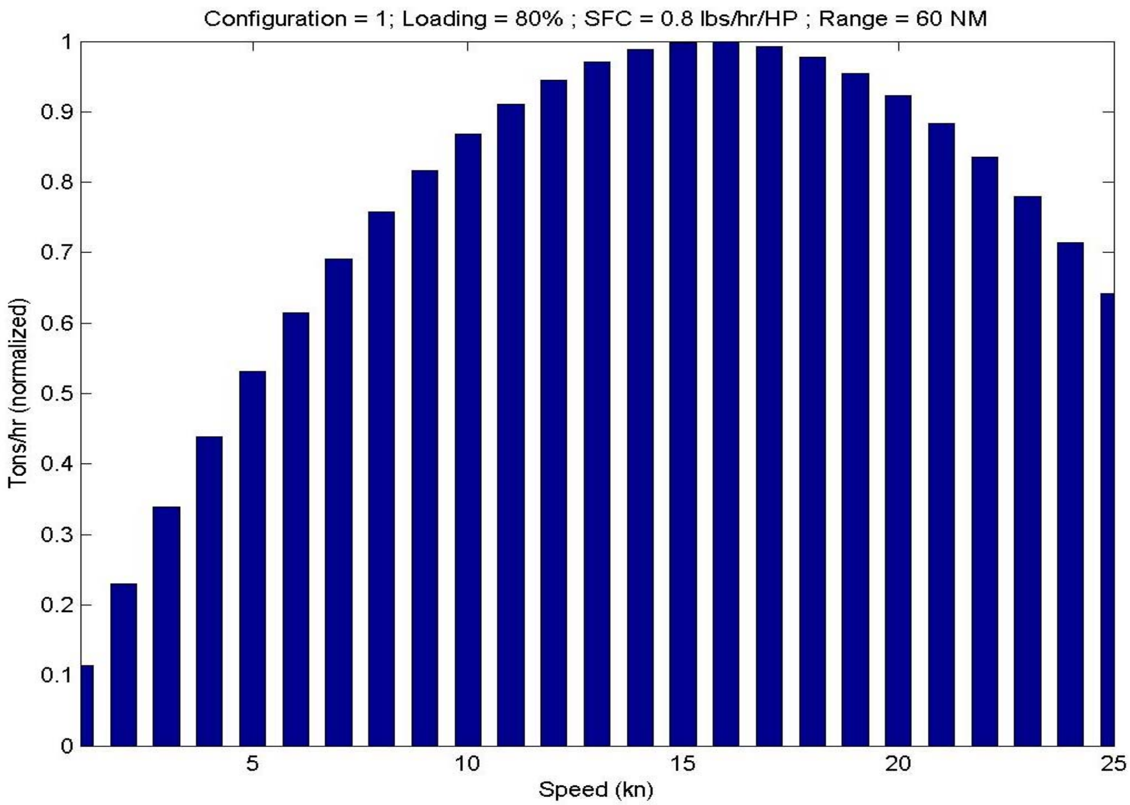

Figure 50. Tons/Hr vs Speed for Bow 1 (80%, 0.80, 60)

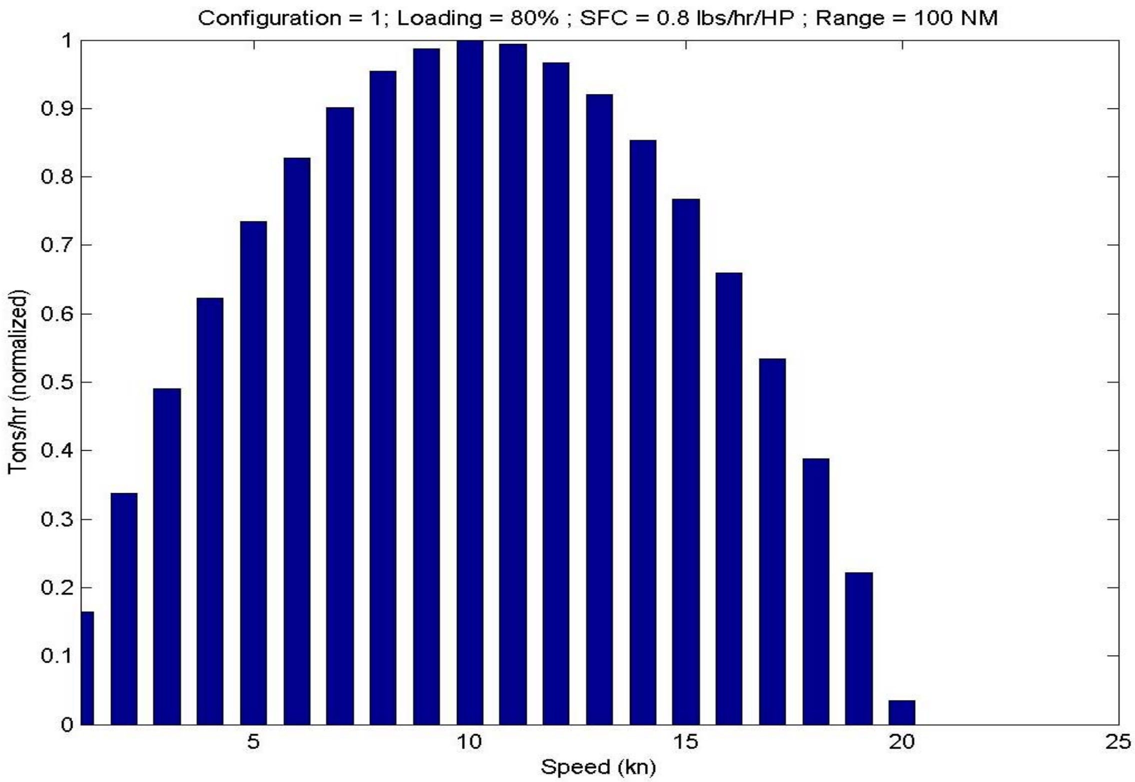

Figure 51. Tons/Hr vs Speed for Bow 1 (80%, 0.80, 100)

If either the SFC or range increases, the payload is no longer a linear function of speed. The maximum payload transferred is most efficient at lower speeds, for those conditions. This is particularly true when holding the loading condition low.

As the SFC and range increase even further, or the loading fraction is decreased, there exists a speed beyond which fuel consumption exceeds the delivered payload. This is noted by the maximum values in the graphs. The point at SFC exceeds delivered payload is referred to as the critical speed for payload delivery. Payload delivery is efficient for speeds less than the critical speed.

2. Bow 5 and Stern 1 (Configuration 6)

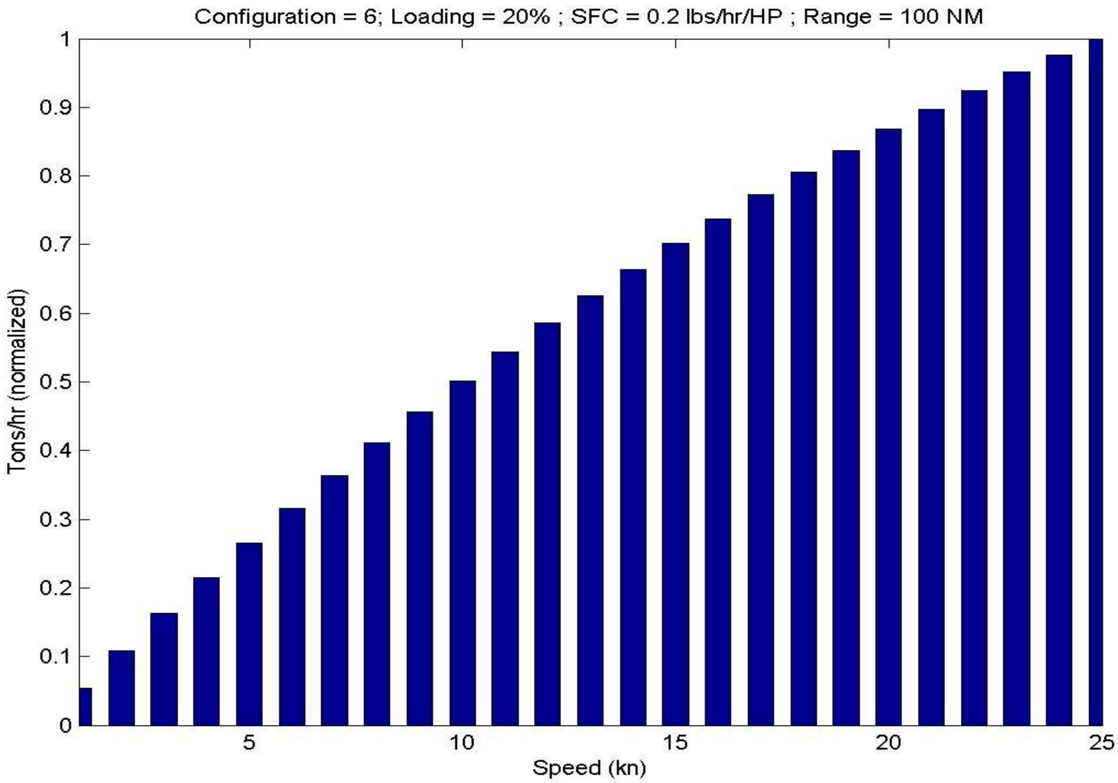

Figure 52. Tons/Hr vs Speed for Bow 5 and Stern1 (20%, 0.20, 100)

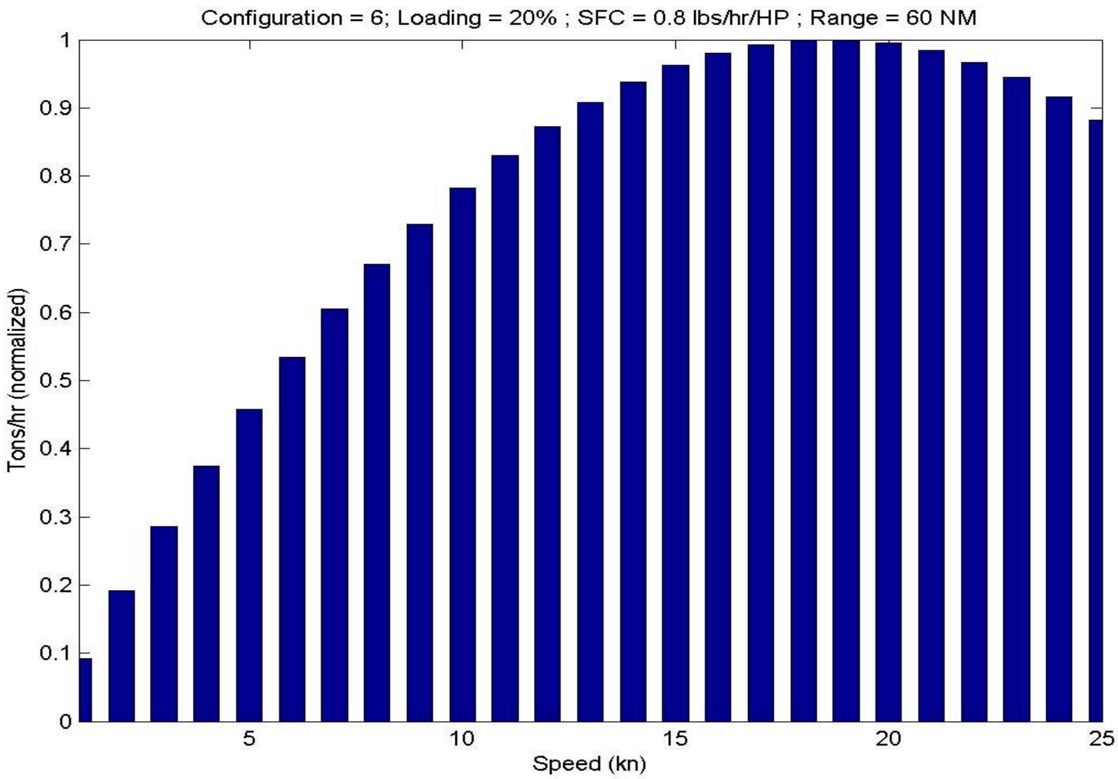

Figure 53. Tons/Hr vs Speed for Bow 5 and Stern1 (20%, 0.80, 60)

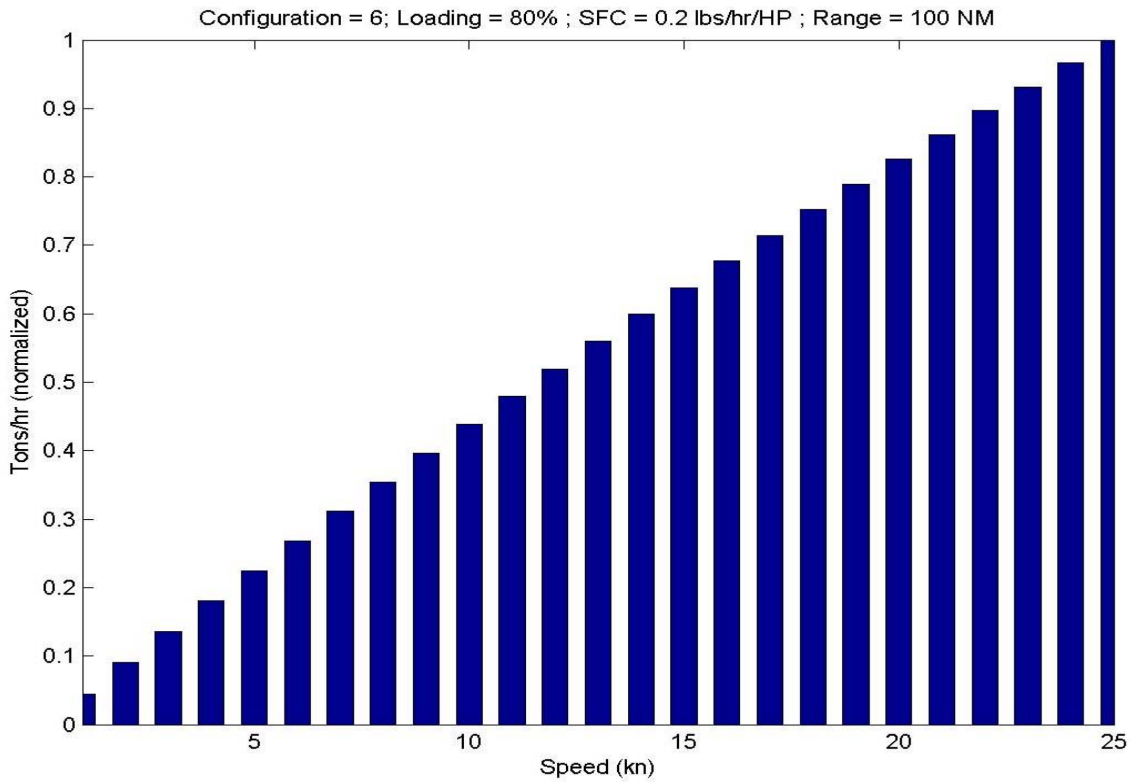

Figure 54. Tons/Hr vs Speed for Bow 5 and Stern1 (80%, 0.20, 100)

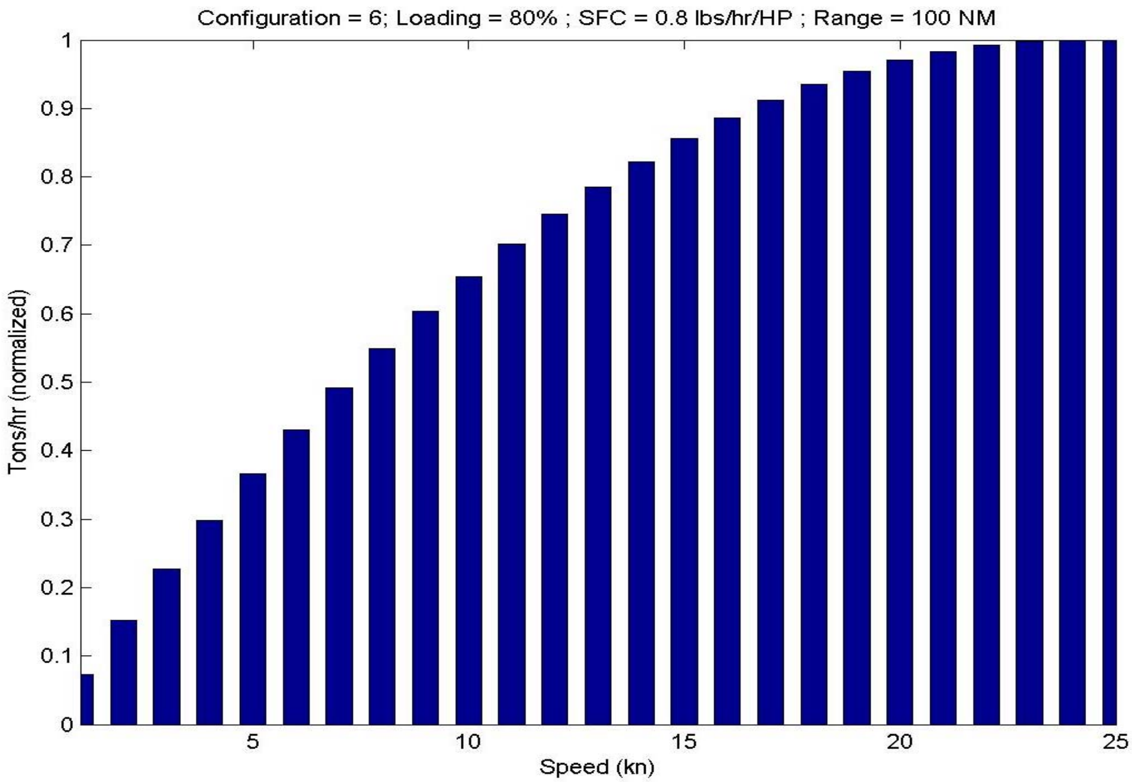

Figure 55. Tons/Hr vs Speed for Bow 5 and Stern1 (80%, 0.80, 100)

As one might expect, the payload transfer becomes a more linear function of speed for bow and/or stern configurations that more efficient. Such configurations result in less resistance and, therefore, less fuel consumption.

3. Color Scale Representation of Normalized Payload for Configuration 1 and Configuration 6

The previous results can be summarized and represented in a visual manner in the figures that follow. In these figures, the normalized payload is represented in a color scale as function of both speed and range. The dark red areas of the graph correspond to the critical values of speed. Speed and range combinations that are appropriate for payload delivery are that of speeds less than critical. It can be seen that the critical speed combinations move towards the lower left corner of the graph as the specific fuel consumption and/or range are increased. For more efficient configurations, such as

configuration 6, the critical speed band has a tendency to move towards the upper right corner of the figure for that hull form.

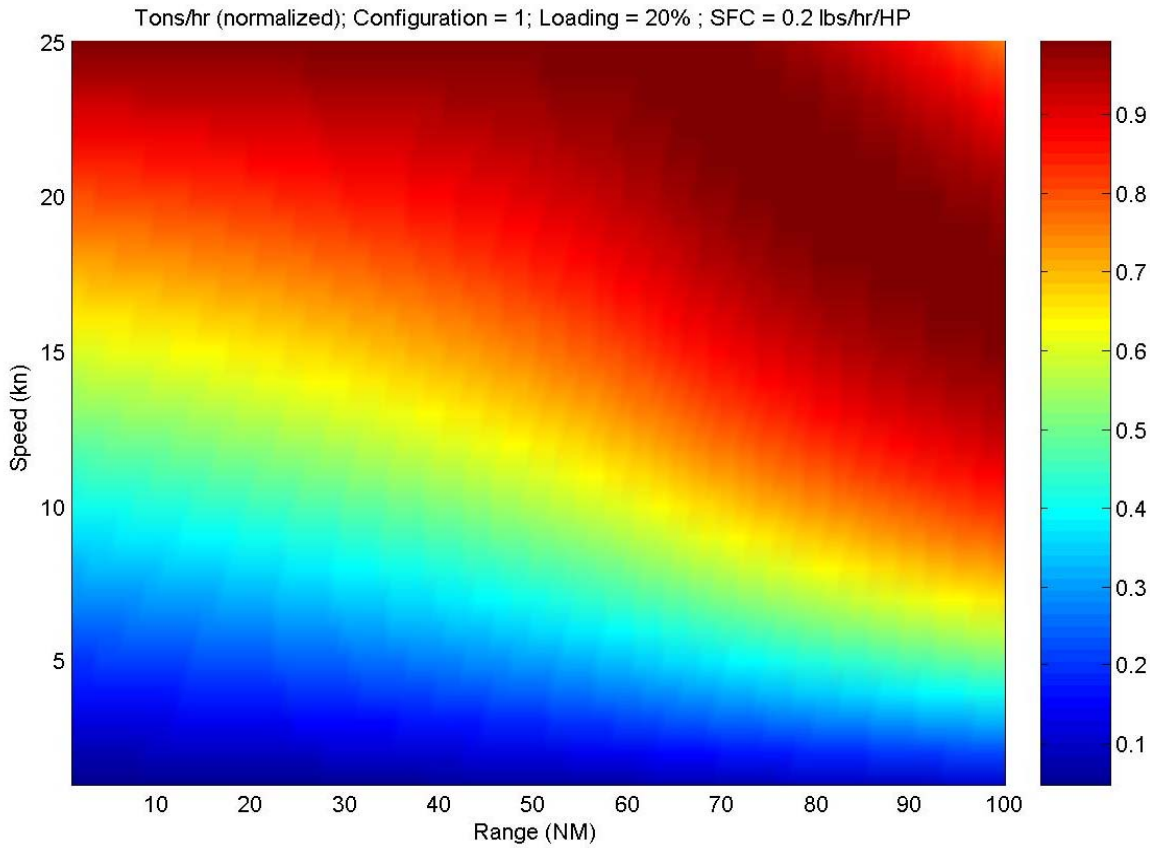

Figure 56. Speed vs Range for Bow 1 (20%, 0.20)

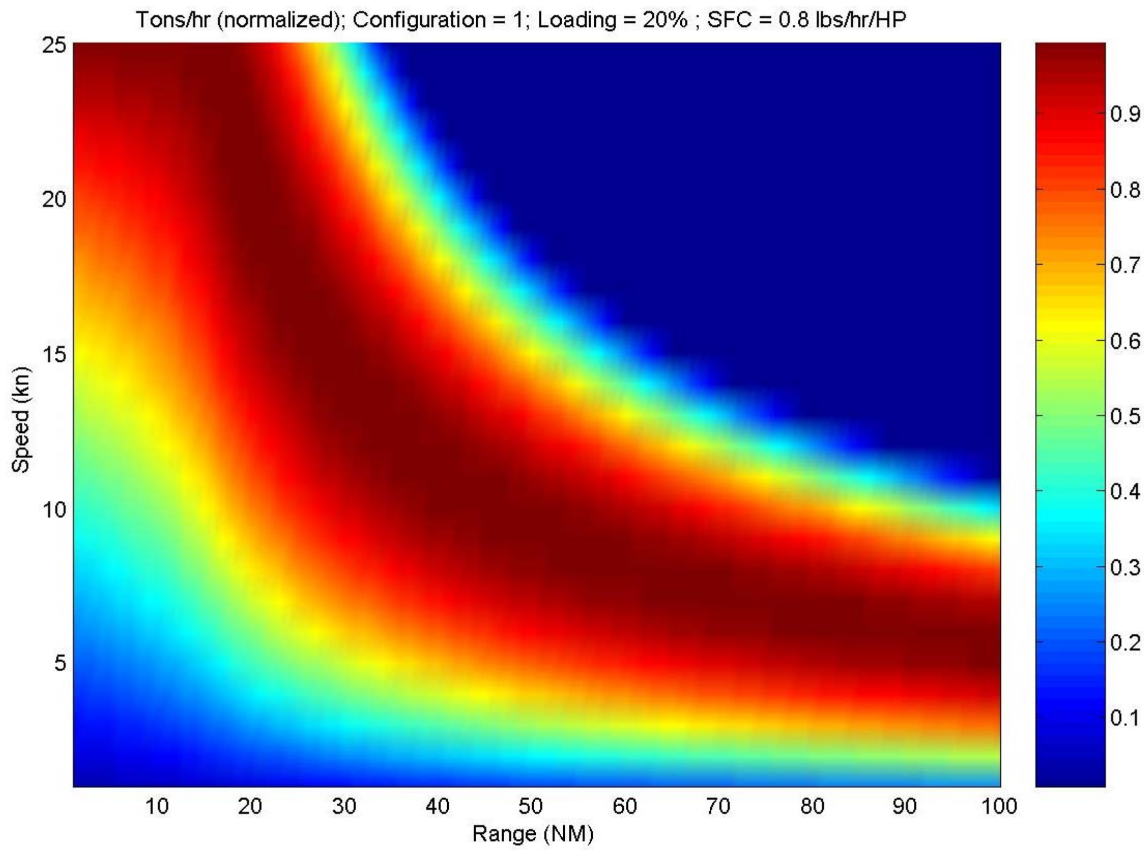

Figure 57. Speed vs Range for Bow 1 (20%, 0.80)

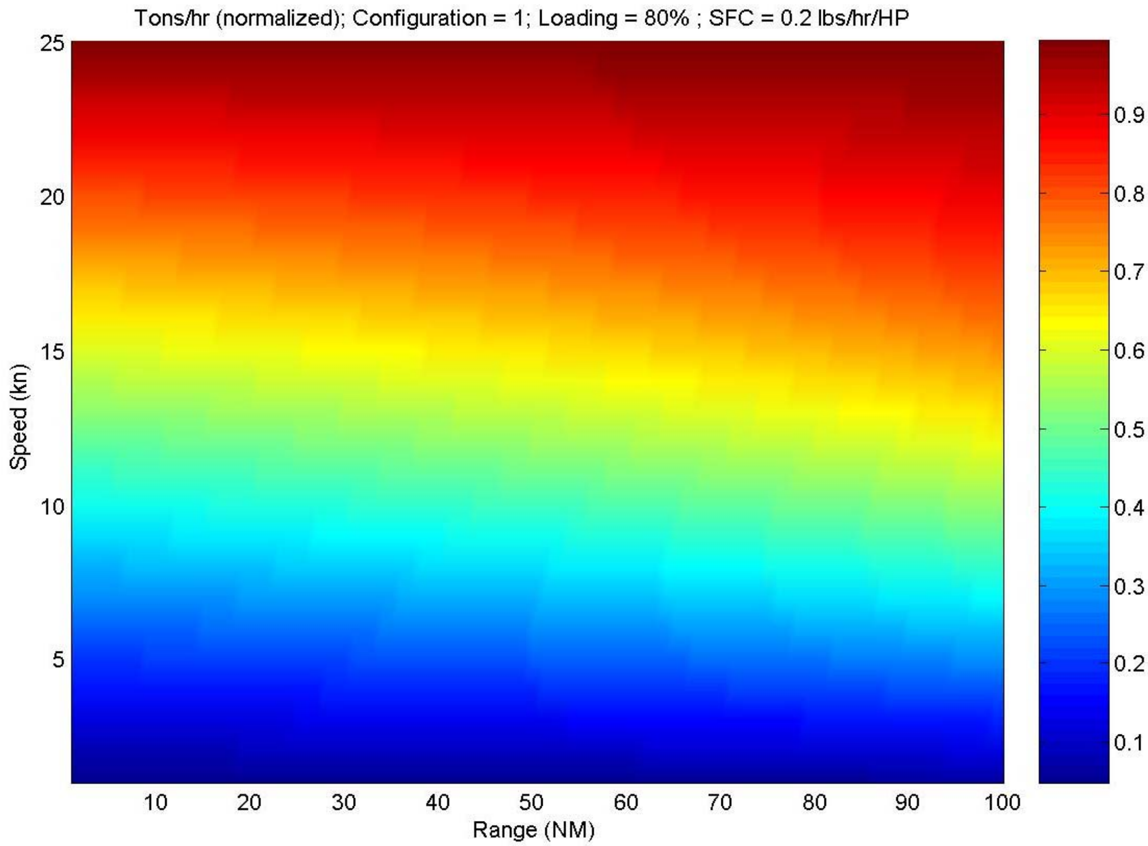

Figure 58. Speed vs Range for Bow 1 (80%, 0.20)

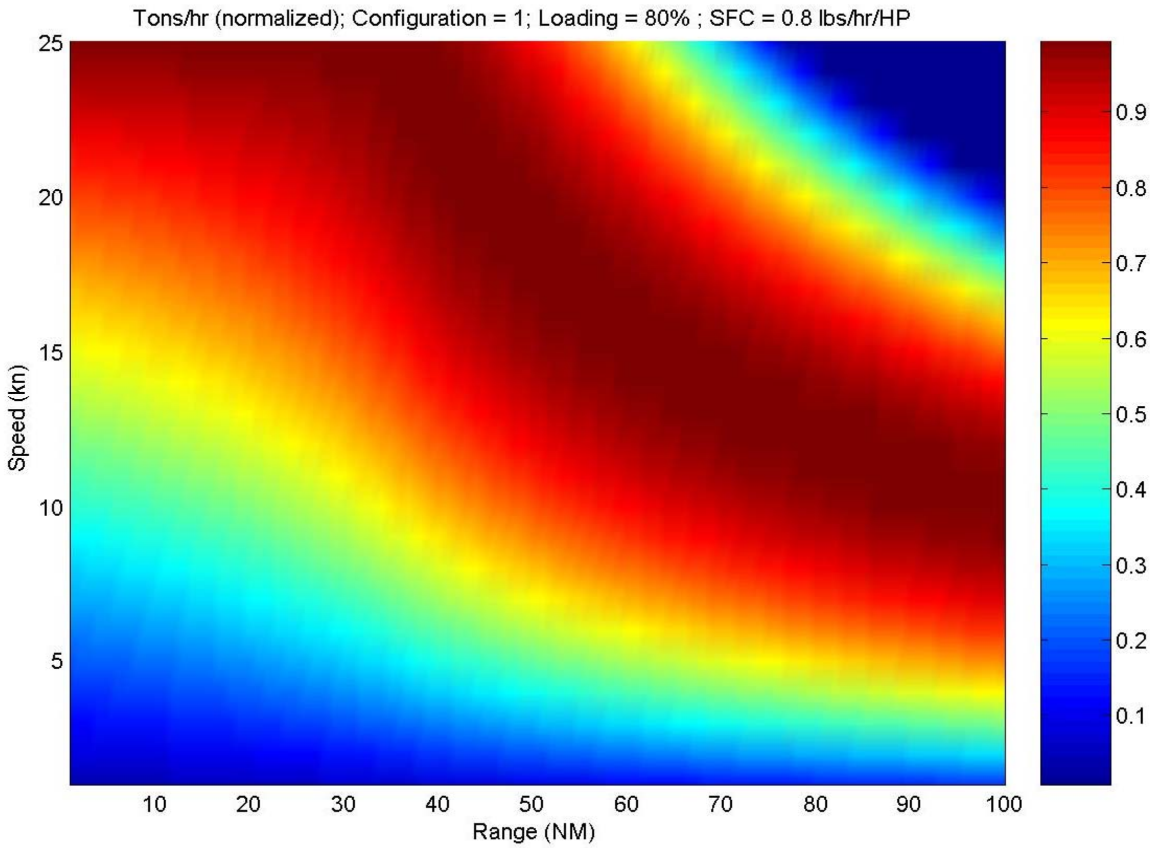

Figure 59. Speed vs Range for Bow 1 (80%, 0.80)

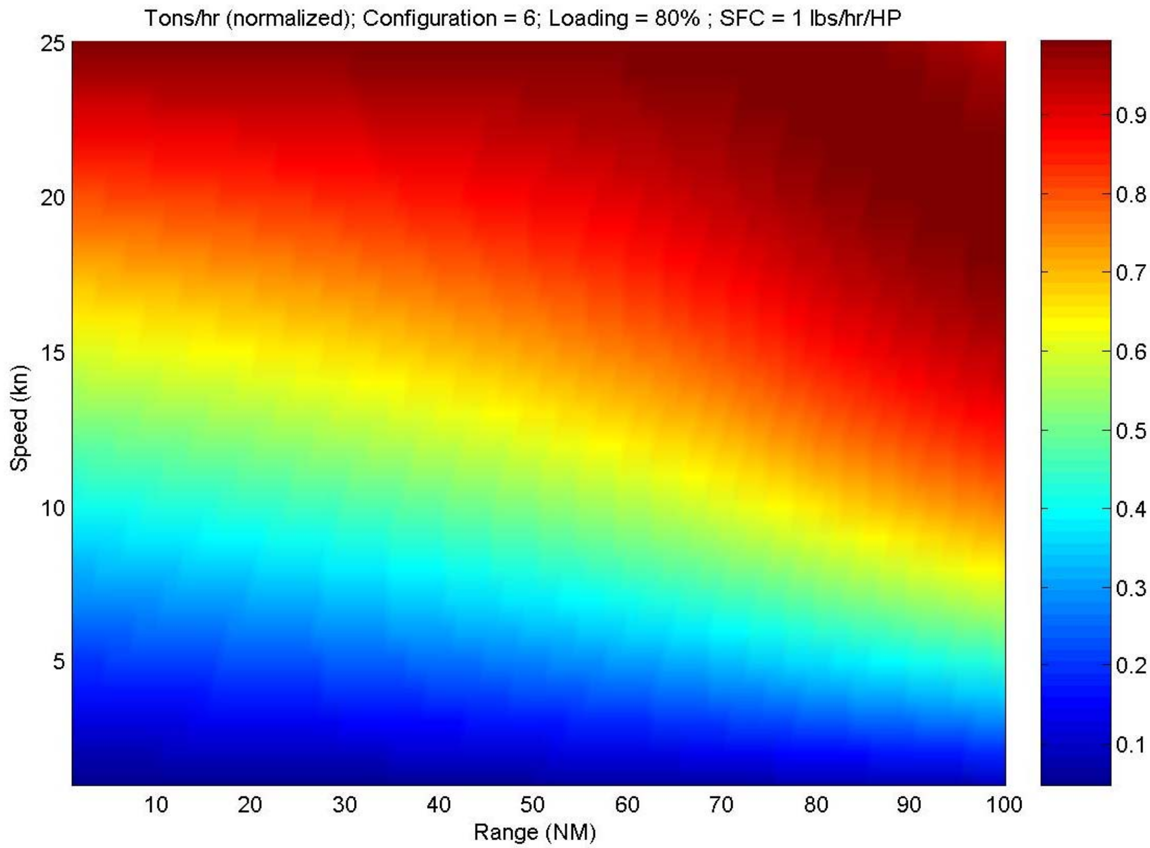

Figure 60. Speed vs Range for Bow 5 and Stern 1 (80%, 1.00)

It should be noted that the previous graphs are in terms of the normalized payload delivery. If one is interested in the actual payload delivery, then figures similar to the ones presented below must be used. Again, it can be seen that there are certain speeds that if they are exceeded, the actual delivered payload transfer is less.

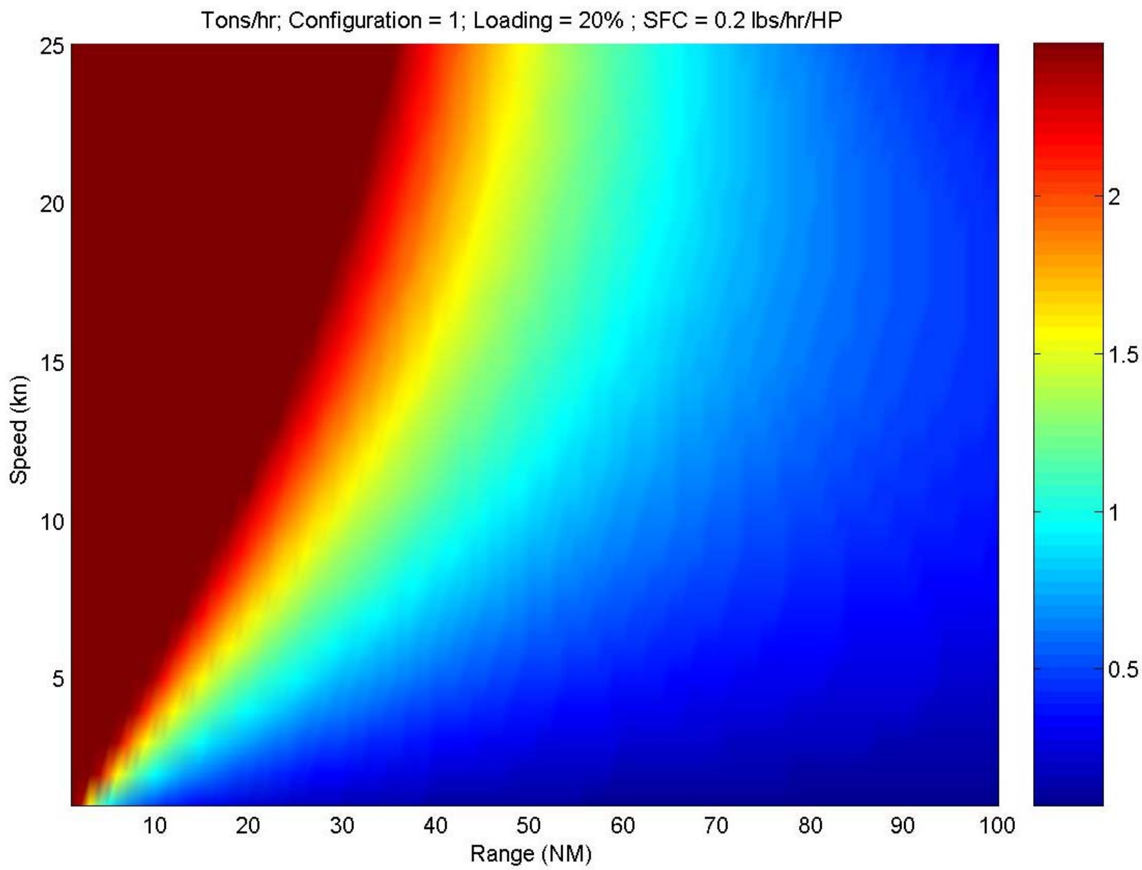

Figure 61. Speed vs Range for Bow 1 (20%, 0.20)

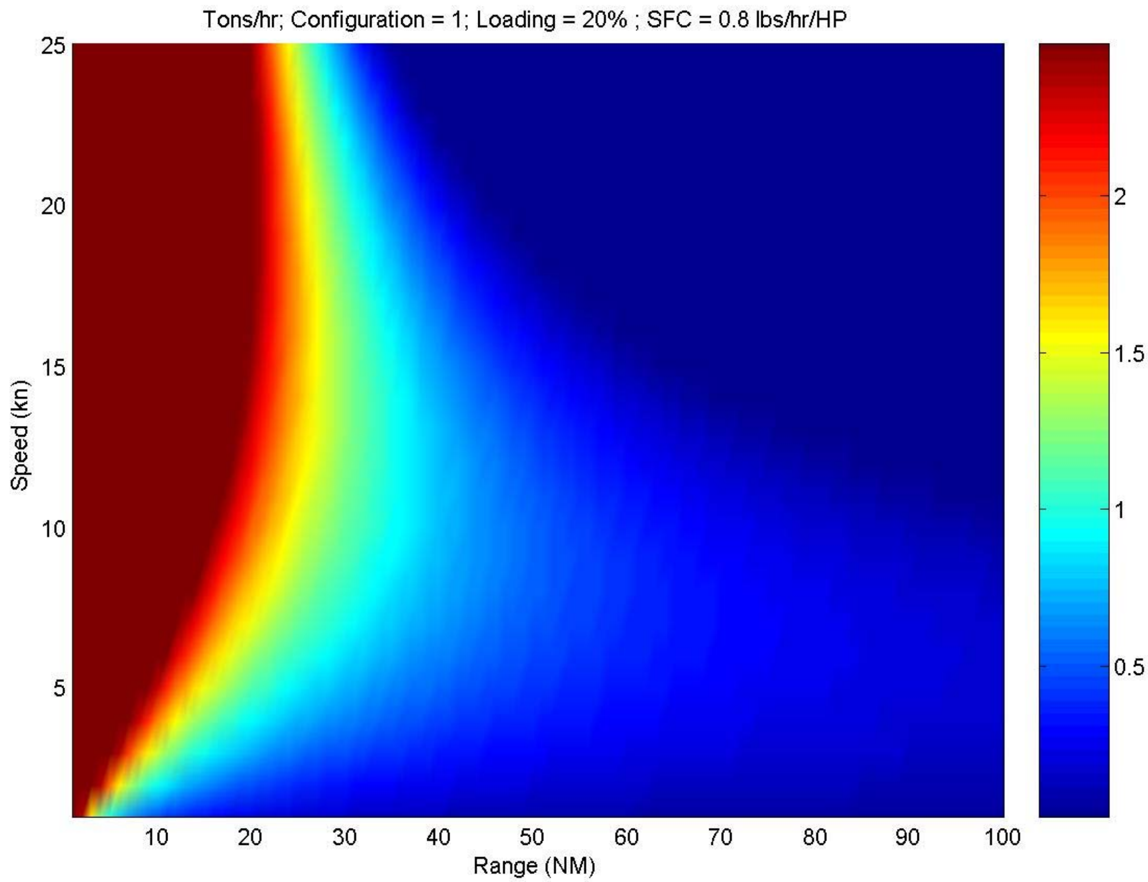

Figure 62. Speed vs Range for Bow 1 (20%, 0.80)

4. Color Scale Representation of Critical Speed Calculations for Configuration 1 and Configuration 6

The following figures summarize the critical speed calculations. The critical speed is shown in a graphical scale as a function of both range and SFC. It can be seen that as the SFC and/or range are increased, or the loading condition is decreased, payload transfer is efficient for lower speeds. As expected, less resistance or more efficient configurations, such as configuration 6, result in greater values for the critical speed. Such configurations can operate at higher speeds and still maintain efficient payload delivery rates.

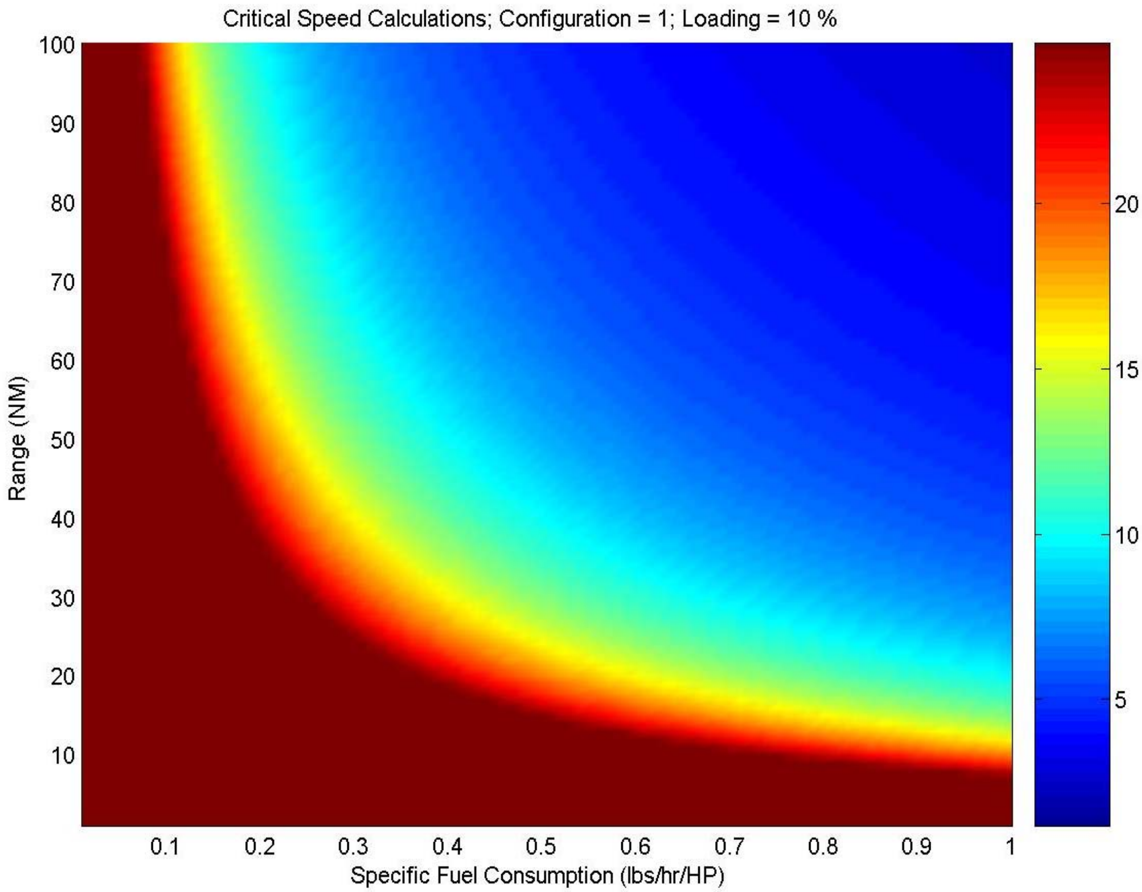

Figure 63. Critical Speed Bow 1 @ 10% Loading

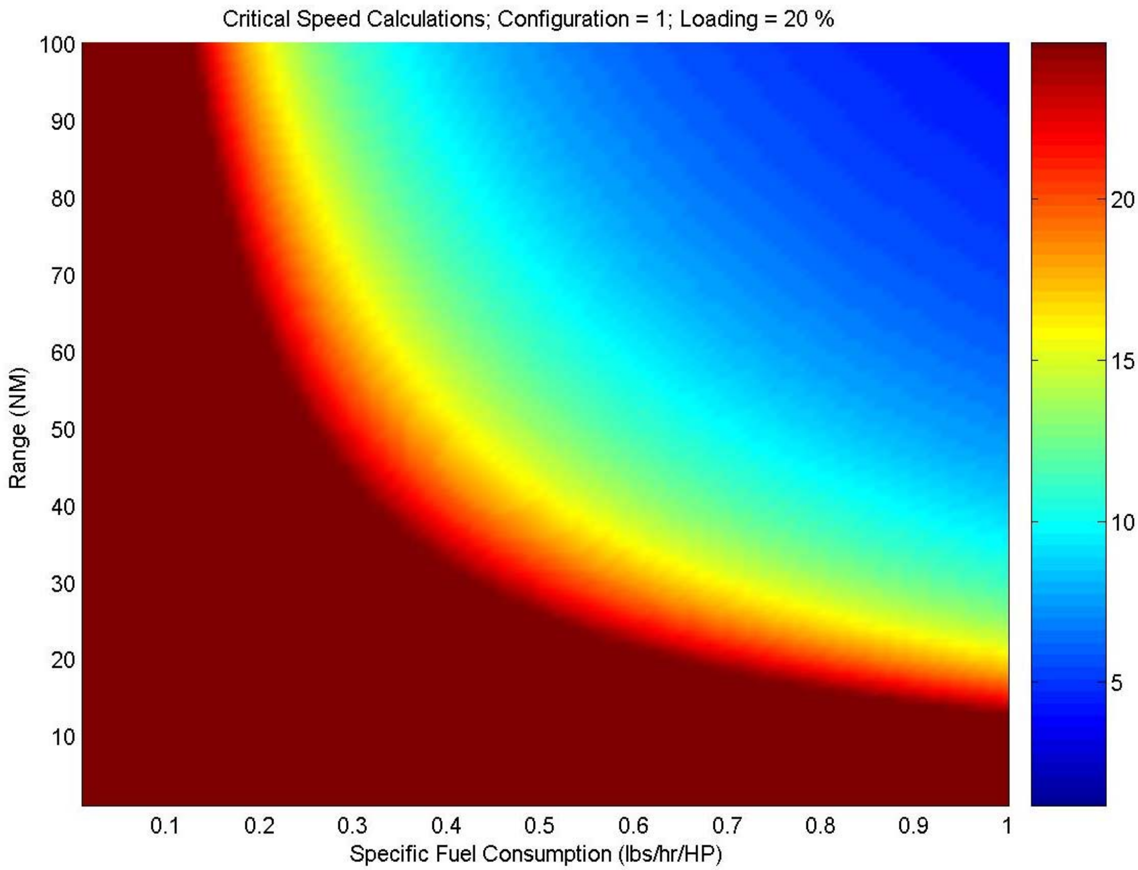

Figure 64. Critical Speed Bow 1 @ 20% Loading

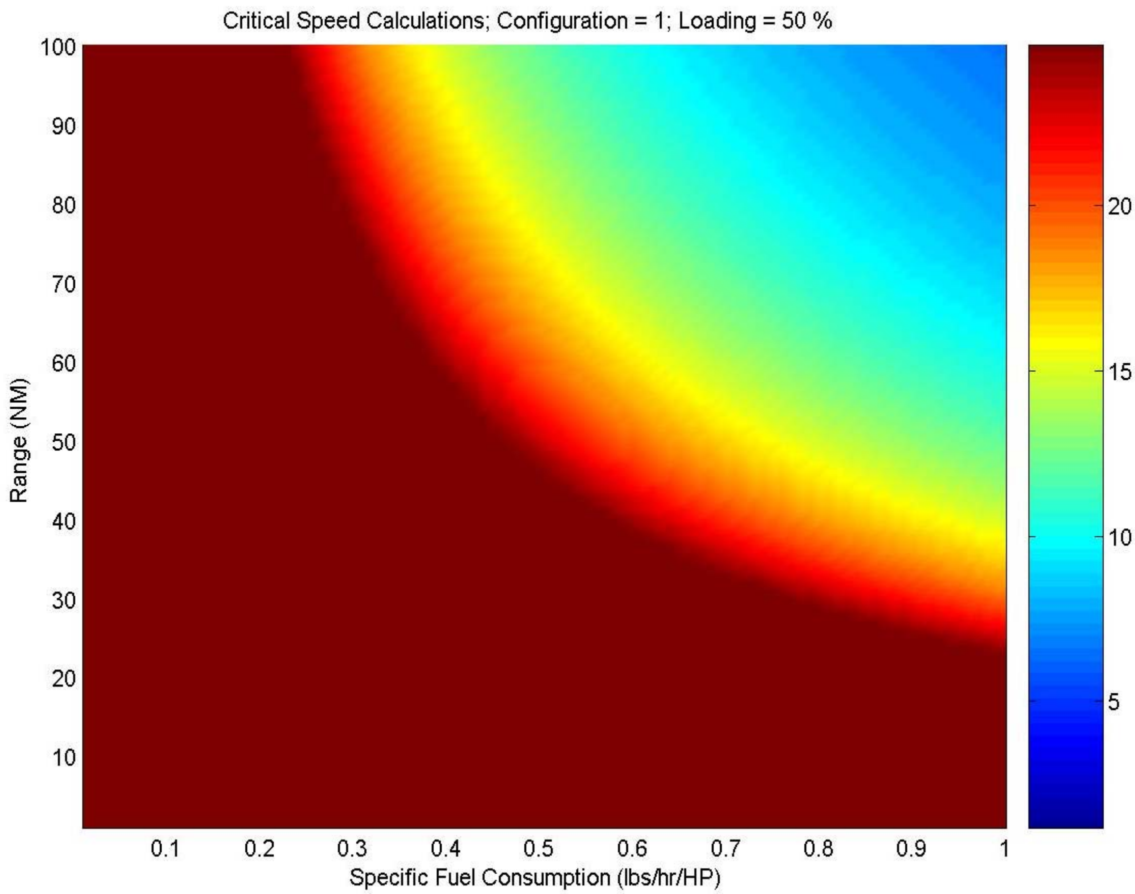

Figure 65. Critical Speed Bow 1 @ 50% Loading

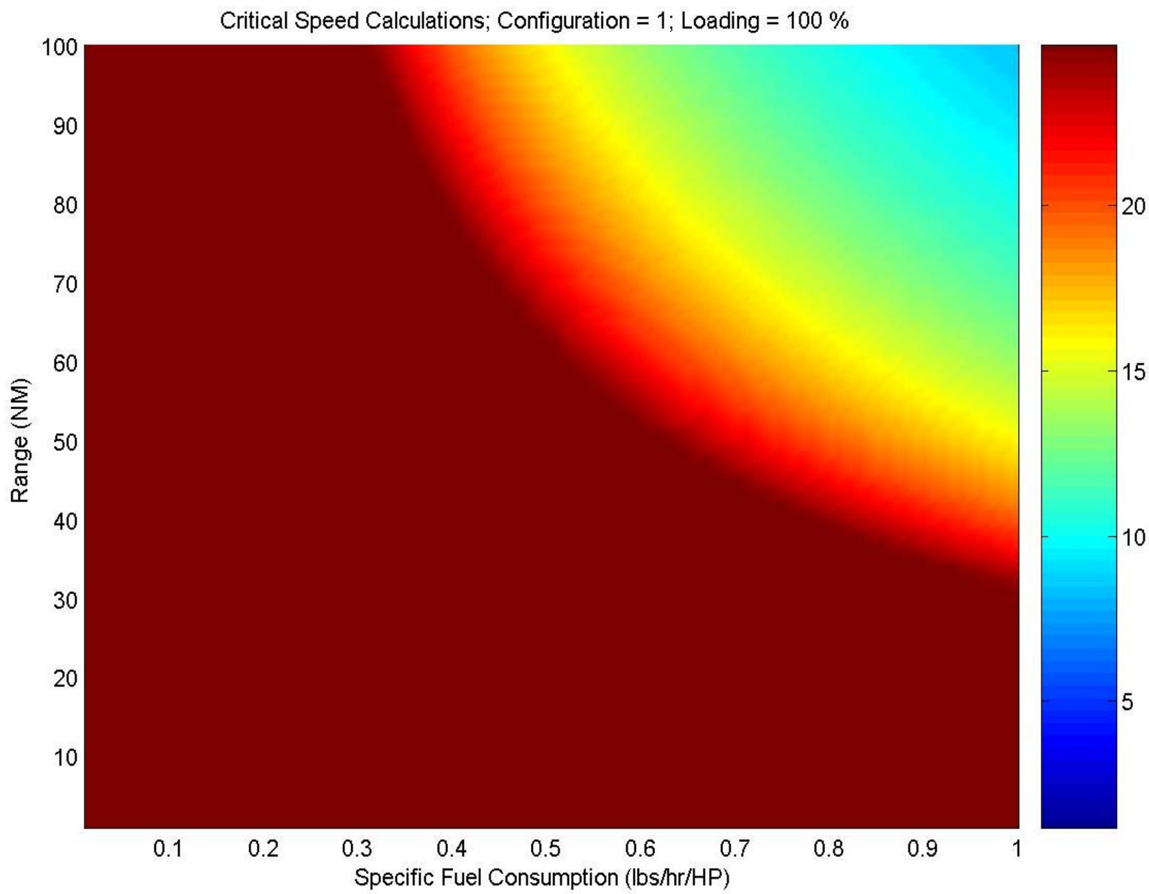

Figure 66. Critical Speed Bow 1 @ 100% Loading

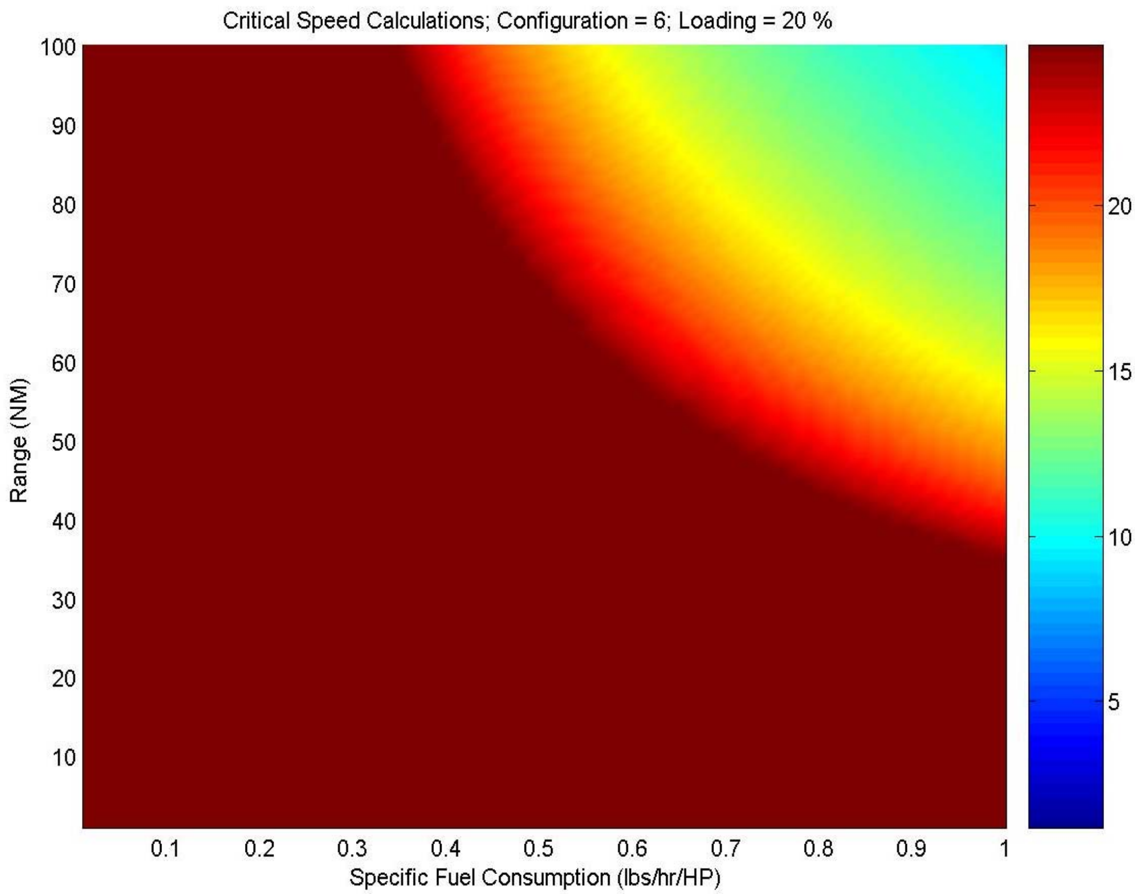

Figure 67. Critical Speed Bow 5 and Stern 1 @ 20% Loading

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VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

The Autonomous Sustainment Cargo Container delivery system is a conceptual idea that is only in testing, but it will prove to be immensely vital to the military community as more and more conflicts are waged in the littorals. Analysis for displacement and draft based on the definitions provided by AEPCO, Inc. for 20 feet containers were conducted. It was proven that an ISO cargo container with the implementation of a bow unit and a stern unit had a dramatic decrease in drag and resistance for the ASCC system as the ISO container traveled through the water. Bow and stern optimization steps were initiated. Starting with the five NSWC Carderock Division bow units, one AEPCO bow unit, and four NSWC Carderock Division stern units, analysis was conducted to determine the greatest performance for any given combination of bow and stern units.

As expected, the data showed that the bow with slight rigidity, Bow 5, combined with Stern 1, was the most efficient. The numerous figures for Configuration 6 in the previous chapter indicate which percent loading factor and specific fuel consumption is optimum for a predetermined range and speed using the ASCC system. With throughput evaluation as the main criteria for this study, all aspects for differing combinations must be examined.

B. RECOMMENDATIONS

Although the results of the analysis for resistance of an ISO cargo container with the implementation of a bow unit and stern unit are of what was expected, there definitely are some other issues with the structure that need close attention. This study lays the ground work for future study and developmental research for an ASCC system. In order to promote future technical development process geared toward this innovative conceptual design, further series of analytical studies must be implemented.

1. A typical ISO cargo container contains gaps and holes within its structure. These cavities include the fork lift holes and also any spacing between the bow unit and stern unit. With these gaps and holes present on the vessel contributing to increased drag and resistance, exactly how much is affected by it is still not clear.

2. Another potential cause for an increase in drag and resistance would the corrugation of the ISO cargo container. Figure 4 shows the typical corrugation than an ISO container possess. Corrugation may cause additional skin friction drag due to wetted surface area as well as that of turbulent flow separation.

3. The possibility of using longer parallel midbody was not discussed throughout the duration of this study. Future analytical reports will need to be conducted to determine and emphasize the possible benefits of choosing a longer vessel with more parallel midbody than a smaller vessel. When discussing about parallel mid-bodies, there are some options. Should a second 20 feet ISO cargo container be added or should a 40 feet container be used? Although an ISO 80 feet container does not exist, how will the 80 feet container compare in resistance to that of 40 feet and should the design be one 80 feet container or two 40 feet containers?

4. Once resistance is finalized, studies involving seakeeping and hydrodynamic stability will need to be thoroughly conducted. These stability tests should also involve differing loading conditions. Model testing in turbulent waters will be needs to determine its seaworthiness. It is highly recommended that a model testing be performed on the ASCC final design concept since model testing is the best reliable source for predicting resistance and seakeeping performance.

5. Knowing that the ASCC will be going into littoral combat areas, one could say that future studies would include the need to analyze the system's survivability rate. However, the need for such a study would be very low considering that the ASCC system is of minimal cost.

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APPENDIX A

A. APPENDIX A: SECTION 1:

1. Drag Coefficient versus Froude Number Calculations

	B/T = 3.0			B/T = 2.0	
	Model 1	Model 6		Model 1	Model 6
Fn	C_D	C_D	Fn	C_D	C_D
0.0750		0.200	0.0750		0.240
0.0875		0.185	0.0875		0.225
0.1000	0.405	0.175	0.1000	0.590	0.205
0.1125	0.430	0.165	0.1125	0.590	0.195
0.1250	0.450	0.155	0.1250	0.590	0.180
0.1375	0.465	0.150	0.1375	0.585	0.160
0.1500	0.480	0.135	0.1500	0.580	0.155
0.1625	0.495	0.125	0.1625	0.575	0.145
0.1750	0.510	0.115	0.1750	0.575	0.140
0.1875	0.520	0.110	0.1875	0.575	0.135
0.2000	0.535	0.110	0.2000	0.575	0.130
0.2125	0.550	0.120	0.2125	0.570	0.120
0.2250	0.565	0.140	0.2250	0.570	0.100
0.2375	0.580	0.160	0.2375	0.580	0.110
0.2500	0.605	0.165	0.2500	0.585	0.145
0.2625	0.625	0.180	0.2625	0.595	0.195
0.2750	0.650	0.190	0.2750	0.605	0.230
0.2875	0.660	0.210	0.2875	0.615	0.240
0.3000	0.685	0.240	0.3000	0.620	0.240
0.3125	0.705	0.290	0.3125	0.635	0.250
0.3250	0.740	0.350	0.3250	0.650	0.290
0.3375	0.765	0.420	0.3375	0.670	0.380
0.3500	0.790	0.440	0.3500	0.685	0.460
0.3625	0.825	0.465	0.3625	0.710	0.500
0.3750	0.850	0.470	0.3750	0.730	0.505
0.3875	0.890	0.475	0.3875	0.750	0.500
0.4000	0.925	0.475	0.4000	0.770	0.485
0.4125	0.965	0.475	0.4125	0.790	0.460
0.4250	1.010	0.500	0.4250	0.805	0.420

2. Bow Variants of Horsepower versus Froude Number

	PE [hp]				
Fn	**Bow 1**	**Bow 2**	**Bow 3**	**Bow 4**	**Bow 5**
0.20	12.0	39.8	12.0	8.1	11.3
0.20	12.9	43.0	12.9	8.4	12.2
0.21	14.2	47.0	14.2	8.9	13.4
0.21	15.4	50.6	15.3	9.4	14.5
0.22	17.0	55.2	16.8	10.0	16.1
0.22	19.2	60.9	18.8	11.0	18.1
0.23	21.3	66.4	20.9	12.0	20.1
0.24	24.4	73.9	23.8	13.7	23.2
0.24	28.1	82.2	27.3	15.8	26.8
0.25	32.4	91.1	31.5	18.5	30.9
0.26	37.3	102.2	36.4	22.0	36.2
0.27	43.9	115.3	42.5	26.4	42.5
0.28	51.4	131.0	49.7	32.0	50.2
0.29	61.6	151.4	58.7	39.4	59.2
0.30	73.9	175.7	68.9	48.4	70.1
0.32	88.8	203.8	81.3	59.9	81.5
0.33	108.2	240.4	96.4	74.7	96.1
0.35	135.1	290.6	116.6	96.0	114.6
0.38	170.7	353.1	143.0	124.4	137.5
0.41	220.2	440.4	179.8	164.8	170.4
0.45	294.0	567.3	236.5	226.2	220.9
0.50	405.3	762.4	326.4	323.1	302.3
0.53	459.7	861.3	372.6	371.5	344.6
0.55	517.6	970.4	419.4	421.3	390.1
0.58	578.9	1083.5	472.3	474.7	435.3
0.60	643.5	1202.3	524.9	528.0	486.7
0.63	707.3	1329.7	575.5	583.9	536.7
0.66	786.3	1493.1	642.1	652.3	602.3

3. Bow Variants of Total Drag Coefficient versus Froude Number

	C_T				
Fn	**B1**	**B2**	**B3**	**B4**	**B5**
0.2000	0.0911	0.3740	0.0826	0.0574	0.0769
0.2040	0.0926	0.3800	0.0840	0.0565	0.0785
0.2090	0.0945	0.3870	0.0856	0.0556	0.0800
0.2130	0.0966	0.3930	0.0874	0.0551	0.0821
0.2180	0.0996	0.4000	0.0896	0.0549	0.0846
0.2240	0.1040	0.4070	0.0924	0.0554	0.0877

0.2290	0.1080	0.4150	0.0959	0.0569	0.0915
0.2360	0.1130	0.4220	0.1000	0.0593	0.0963
0.2430	0.1190	0.4300	0.1050	0.0627	0.1020
0.2500	0.1260	0.4380	0.1110	0.0672	0.1080
0.2580	0.1320	0.4470	0.1170	0.0727	0.1150
0.2670	0.1400	0.4550	0.1230	0.0789	0.1220
0.2770	0.1470	0.4630	0.1290	0.0857	0.1290
0.2890	0.1550	0.4710	0.1340	0.0929	0.1340
0.3020	0.1630	0.4790	0.1380	0.1000	0.1390
0.3160	0.1710	0.4850	0.1420	0.1080	0.1410
0.3330	0.1780	0.4890	0.1440	0.1150	0.1420
0.3540	0.1850	0.4920	0.1450	0.1230	0.1410
0.3780	0.1920	0.4910	0.1460	0.1310	0.1390
0.4080	0.1970	0.4870	0.1460	0.1380	0.1370
0.4470	0.2000	0.4770	0.1460	0.1440	0.1350
0.5000	0.1970	0.4580	0.1440	0.1470	0.1320
0.5250	0.1930	0.4470	0.1420	0.1460	0.1300
0.5500	0.1890	0.4380	0.1390	0.1440	0.1280
0.5750	0.1850	0.4280	0.1370	0.1420	0.1250
0.6000	0.1810	0.4180	0.1340	0.1390	0.1230
0.6250	0.1760	0.4090	0.1300	0.1360	0.1200
0.6550	0.1700	0.3990	0.1260	0.1320	0.1170

4. Froude Number versus Total Drag and Effective Horsepower For Bow 5 and Stern 1

C_T		**EHP**
Fn	S1B5	Bow 5 with Stern 1
0.113	0.01	0.390636
0.114	0.01	0.405304
0.115	0.01	0.424159
0.115	0.01	0.430635
0.116	0.01	0.447505
0.117	0.01	0.458042
0.118	0.01	0.462308
0.119	0.01	0.474162
0.12	0.01	0.499092
0.12	0.01	0.510742
0.121	0.01	0.534931
0.122	0.01	0.553459
0.123	0.01	0.554635
0.124	0.01	0.56692
0.125	0.01	0.597379
0.126	0.01	0.630995

0.127	0.01	0.666489
0.128	0.01	0.697984
0.129	0.01	0.704569
0.13	0.01	0.700033
0.131	0.01	0.724289
0.132	0.01	0.769566
0.134	0.01	0.827276
0.135	0.01	0.872999
0.136	0.01	0.901468
0.137	0.01	0.88683
0.139	0.01	0.910039
0.14	0.01	0.959031
0.141	0.01	1.004595
0.143	0.01	1.079081
0.144	0.01	1.112472
0.146	0.01	1.126344
0.147	0.01	1.10569
0.149	0.01	1.185476
0.151	0.01	1.319371
0.152	0.01	1.408061
0.154	0.01	1.503255
0.156	0.01	1.522175
0.158	0.01	1.455516
0.16	0.01	1.496958
0.162	0.01	1.659396
0.164	0.01	1.846826
0.167	0.01	2.098773
0.169	0.01	2.260718
0.171	0.01	2.199999
0.174	0.01	2.186986
0.177	0.01	2.361095
0.18	0.01	2.69013
0.183	0.01	3.131325
0.186	0.02	3.630349
0.189	0.02	3.832815
0.192	0.02	3.867558
0.196	0.02	4.381517
0.2	0.02	5.166231
0.204	0.02	5.813802
0.209	0.02	6.770139
0.213	0.02	7.440651
0.218	0.02	7.572671
0.224	0.02	8.693866
0.229	0.03	11.63273

0.236	0.03	15.01773
0.243	0.04	18.07422
0.25	0.04	20.90132
0.258	0.03	21.08374
0.267	0.03	18.84302
0.277	0.03	21.56839
0.289	0.04	31.86023
0.302	0.05	45.44501
0.316	0.06	63.14701
0.333	0.06	81.36483
0.354	0.05	83.42536
0.378	0.04	67.84082
0.408	0.03	60.24665
0.447	0.02	74.15678
0.5	0.03	117.0918
0.505	0.03	122.9246
0.51	0.03	128.4948
0.515	0.03	134.2499
0.52	0.03	139.6949
0.525	0.03	145.8172
0.53	0.03	151.6079
0.535	0.03	157.5694
0.54	0.03	163.7048
0.545	0.03	170.0175
0.55	0.03	176.511
0.555	0.03	183.1885
0.56	0.03	190.0537
0.565	0.03	196.4699
0.57	0.03	203.0465
0.575	0.03	209.1114
0.58	0.03	215.3063
0.585	0.03	221.6331
0.59	0.03	228.0934
0.595	0.03	233.9417
0.6	0.03	239.8891
0.605	0.03	245.9364
0.61	0.03	252.0846
0.615	0.03	258.3343
0.62	0.03	263.8409
0.625	0.03	270.2757

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APPENDIX B

A. FOR FIGURE 13 MODEL M6-1 AND M6-2

			Resistance Calculations	
Fn		**Model 1 [lbs]**	**Model 6-1**	**Model 6-2**
0.1000		0.4072	0.1448	0.2551
0.1125		0.5154	0.1727	0.3071
0.1250		0.6363	0.2003	0.3499
0.1375		0.7634	0.2346	0.3764
0.1500		0.9007	0.2513	0.4339
0.1625		1.0480	0.2731	0.4764
0.1750		1.2154	0.2913	0.5335
0.1875		1.3952	0.3199	0.5905
0.2000		1.5875	0.3640	0.6470
0.2125		1.7765	0.4483	0.6742
0.2250		1.9917	0.5863	0.6299
0.2375		2.2580	0.7466	0.7720
0.2500		2.5235	0.8531	1.1276
0.2625		2.8298	1.0260	1.6719
0.2750		3.1579	1.1886	2.1642
0.2875		3.5085	1.4359	2.4683
0.3000		3.8513	1.7868	2.6876
0.3125		4.2801	2.3427	3.0378
0.3250		4.7387	3.0582	3.8113
0.3375		5.2674	3.9575	5.3857
0.3500		5.7917	4.4588	7.0114
0.3625		6.4395	5.0547	8.1752
0.3750		7.0853	5.4675	8.8362
0.3875		7.7729	5.9002	9.3417
0.4000		8.5033	6.2870	9.6555
0.4125		9.2779	6.6860	9.7391
0.4250		10.0357	7.4709	9.4393

M6-1 to Full 20' ISO	M6-2 to Full 20' ISO	M1 Speed	M1 to Bare 20' ISO
PEs [hp]	PEs [hp]	Vs [kts]	PEs [hp]
0.202	0.406	1.498	0.531
0.270	0.549	1.686	0.758
0.344	0.690	1.873	1.041
0.443	0.803	2.060	1.376
0.503	1.009	2.248	1.773
0.580	1.191	2.435	2.236
0.649	1.432	2.622	2.796
0.755	1.693	2.809	3.443
0.925	1.971	2.997	4.182
1.265	2.153	3.184	4.975
1.860	2.041	3.371	5.910
2.608	2.720	3.559	7.083
3.173	4.442	3.746	8.341
4.101	7.235	3.933	9.833
5.046	10.006	4.121	11.510
6.508	11.995	4.308	13.385
8.648	13.644	4.495	15.343
12.125	16.140	4.682	17.785
16.806	21.331	4.870	20.503
22.955	31.866	5.057	23.700
26.933	43.449	5.244	27.053
31.765	52.676	5.432	31.198
35.591	58.944	5.619	35.551
39.738	64.392	5.806	40.343
43.734	68.643	5.994	45.602
47.990	71.271	6.181	51.358
55.448	70.913	6.368	57.277

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